Digital Chart of the World

Development of the Digital Chart of the World

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This report summarizes the studies, prototype development, and design decisions undertaken in the development of the Defense Mapping Agency's Vector Product Format (VPF) Military Standard and the new topologically structured global geo-spatial database, the Digital Chart of the World. The VPF is a generic, machine-independent format for Geographic Information System (GIS) data designed for use by diverse software systems. This format will be used by DMA for the provision of all future geospatial vector information products. The DCW is a comprehensive 1:1,000,000 scale vector basemap of the world. It consists of cartographic, attribute, and textual data stored on compact disc read only memory (CD-ROM) utilizing the VPF. The report covers the objectives, study methodology, and conclusions for each phase of the development effort. It covers design and prototyping, special studies, standards development, VPFVIEW software development, DCW database production, quality assurance, and other VPF product development.

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Chapter 1. Project Summary

1.1 Introduction

The Digital Chart of the World (DCW) is a topologically structured global vector database developed by Environmental Systems Research Institute, Inc. (ESRI) for the Defense Mapping Agency (DMA) to support global scientific and military analysis. Completed in 1992 and now available for public purchase (Appendix A), it contains 1.7 gigabytes of topological data, the largest spatial database ever designed specifically for public dissemination on the Compact Disc–Read-Only Memory (CD–ROM) medium. The database stores georelational attributes organized into seventeen thematic layers designed for Geographic Information System (GIS) applications; the layers include political boundaries, populated places, road and railroad networks, land cover, drainage, elevation contours, ocean features, and data quality. The source data were 276 charts in the Operational Navigation Chart (ONC) and (for Antarctica) the Jet Navigation Chart (JNC) series.

Even though the DCW database makes a significant contribution to global military and scientific analysis by itself, the most significant outcome of the DCW project was the development of a generic, machine-independent format for GIS data that allows data prepared in accordance with it to be used by diverse software systems. Known as Vector Product Format (VPF), this data format was implemented in the DCW database and will be used for the vector data products developed by DMA (and potentially other organizations) in the future. These products will allow DMA's data users—the U.S. Department of Defense, mapping organizations in NATO-member countries, the U.S. intelligence community, and the International Hydrographic Community—to establish applications software to read data from a common format. Through promotion of a common understanding of spatial vector data, VPF thus promotes interoperability between diverse data users.

As a generic data format, VPF has been incorporated into the Digital Geographic Information Exchange Standard (DIGEST) by an international standards committee known as the Digital Geographic Information Working Group (DGIWG), which includes representatives from thirteen countries in Europe and North America. Under DIGEST, VPF is known as Vector Relational Format (VRF).

The DCW project was a multinational effort with participation by military mapping organizations from Australia, Canada, the United Kingdom, and the United States and civilian mapping organizations from Canada and the United States. ESRI organized and coordinated periodic design reviews as part of the project. During these meetings, ESRI presented the results of the most recent prototyping activity and discussed the current status of the design. These meetings also provided a forum for the open discussion and technical review of ESRI's work. In addition to DMA and the participating international organizations, others in attendance included representatives from United States Army Corps of Engineers (USACE) laboratories, the Naval Research Laboratory (NRL), the Naval Ocean Systems Center (NOSC), the National Oceanographic and Atmospheric Administration (NOAA), U.S. intelligence agencies, and the United States Geological Survey (USGS).

In addition to the development of a standard data format and the production of the DCW database, the DCW project resulted in the development of a standard production process for the creation and subsequent maintenance of the DCW database and the development of an applications software package (known as VPFVIEW) for the display and demonstration of the DCW and other VPF databases. As another outgrowth of the project, in late 1991 ESRI began to develop two additional VPF database prototypes—the Digital Nautical Chart (DNC) and the Vector Smart Map (VSM).

1.2 Chronological Overview

For purposes of this report, the DCW project can be considered to have three phases: DCW design and prototyping, DCW production, and the development of two additional VPF-compliant prototypes.

During the design and prototyping phase (October 1989 to January 1991), DCW product requirements were refined and tested in a series of prototypes; the final design decisions were embodied in the DCW product specification (see Appendix B). The prototypes also helped establish and refine the DCW production methodology, the VPFVIEW software, and the VPF standard.

During the production phase (September 1990 to April 1992), the full-scale production of the DCW took place; production was followed by product duplication and distribution (May 1992 to August 1992).

During the third phase (January 1992 through December 1992), ESRI is prototyping the VSM and DNC, two additional DMA product series that have been prepared in accordance with VPF.

1.3 Phase I—Design and Prototyping

1.3.1 Prototype Development

Four DCW database prototypes were designed and produced for the purpose of evaluating design decisions, evaluating the VPFVIEW functions, establishing database automation procedures, and implementing VPF. The exercise of the prototypes, and the ideas and information generated by their review, were intended to allow the incremental development of the design of the DCW. Each of these prototypes was itself an interim product, which, when disseminated to the various participants, provided an opportunity for feedback with respect to product content, design, and application programs.

Prototype 1 (developed from October 1989 to December 1989) was used to test and demonstrate a mockup of the DCW for a small portion of ONC G-18. PC ARC/INFO software was used for Prototype 1 because it provided ready-made display and query capabilities. Applications software was written using the Simple Macro Language to demonstrate the basic user interface and planned functional capabilities.

Prototype 2 (developed from January 1990 to April 1990) implemented the design concept developed for Prototype 1. The software represented the first prototype of the VPFVIEW software. The database encompassed a larger portion of ONC G-18, small portions of two NOAA charts for Hampton Roads, Virginia, and a small portion of the Killeen, Texas 1:50,000-scale topographic map. These large-scale data sources were used for the database to begin to examine the ability of the software to handle large-scale data. Comments on the first prototype and additional information from the participants in the project were incorporated in this prototype, which focused primarily on the conceptual designs for the DCW and the software.

Prototype 3 (developed from May 1990 to August 1990) fully implemented the VPFVIEW software functions presented in the second prototype. Its development also entailed the establishment of standard database production procedures. Prototype 3 was the first prototype for which data were structured according to VPF and stored on CD–ROM. However, the VPF standard continued to evolve beyond this point. The data sets for this prototype included ONCs G-18 and N-13, JNC 120, the Killeen topographic map, and the nautical charts for Hampton Roads and Harwich, U.K.

Prototype 4 (developed from July 1990 to December 1990) fully implemented the ideas for database redesign and the new VPFVIEW functions added after the comments from the DCW participants were considered. A complete set of Standard Operating Procedures (SOPs) for the DCW database production was developed, since this prototype served as a production dry run. This prototype was the first to contain adjacent map sheets in the database (ONCs E-1, F-1, G-1, and G-2), and so its production entailed the development of preliminary production sheets for edge matching. Submission of this prototype to DMA in September 1990 marked the beginning point for full-scale production of the DCW database.

1.3.2 Special Studies

Several special studies were conducted early in the development of the DCW database. These studies were made to determine the best way to implement the storage of aeronautical information, storage of elevation data, data partitioning (tiling), indexing (how to set the data up for rapid access and retrieval), geographic organization (which portions of the world to include on each CD–ROM), symbolization, and error analysis. The results of these studies were applied to Prototype 4.

1.3.3 Standard Development

Vector product format (which was at first called the Vector Product Standard or VPS) underwent development throughout the prototyping period. The primary objective of the development was to ensure that VPF could be used not only for the DCW, but also for other digital data products being developed within DMA. The development of VPF represented a significant portion of the effort devoted to the DCW project as a whole.

A generic, product-neutral, hardware-independent georelational data model, VPF is designed to support direct usage by GIS software; it is not a data exchange standard. VPF's characteristics enable it to support seamless databases, to model different topologies and topological levels, to support feature- and coverage-based designs, and to store metadata (information about the database itself). It has been adopted as part of a family of standards known as DIGEST.

Within this standard, VPF defines the relational format for vector-based products, and is thus called Vector Relational Format (VRF); the content of VPF and VRF is identical.

A training plan has been developed to transfer VPF technology to DMA. The plan is described briefly in Appendix C.

An additional objective of the DCW prototyping phase—as originally defined in the DCW Statement of Work (SOW)—was to develop applications software that would enable the user to display the DCW database. However, during the prototyping period, the objective for the software expanded to include the generic demonstration of VPF databases. Software functionality also expanded as the result of prototype review; the final VPFVIEW functions include feature selection, graphics display and report, text report, file archive, operations on the DOS system, spatial query, adaptive menuing, map distance measuring functions, and others.

The VPFVIEW–DOS software released with the DCW database was designed to be used on PC-class computers. A UNIX-based version known as VPFVIEW–UNIX was requested by DMA and will be complete by December 1992.

The application of VPFVIEW to other VPF databases such as the DNC and VSM is currently being worked on at ESRI (see the description of Phase III below). These projects are continuing to test the design of VPF and to support its widest possible applicability to other digital vector data.

1.4 Phase II—DCW Database Production and Quality Assurance

1.4.1 Production Procedures

Database production was the most time-consuming and labor-intensive portion of the DCW project. It involved the automation of 276 ONC and JNC source maps to create a topologically structured, geocoded, vector database. Automation was followed by conversion to VPF data structure and storage on CD–ROMs for public dissemination.

One of the requirements of DCW production was that it proceed according to standard operating procedures to be established during the project. Guided by the standards required for the final product, those responsible for production focused on creating production procedures that would use both proven methodologies and new procedures to ensure production efficiency and a high level of quality in the product. In September 1990, after detailed preliminary production procedures were developed for Prototypes 3 and 4, full-scale production began. The production period consisted of ramp-up, full production, and ramp-down periods. During the period of full production, nineteen Sun SPARC workstations were utilized on a two-shift basis to conduct most production operations. Production was completed in April of 1992.

During product packaging (May 1992 to August 1992), the four preliminary DCW CD–ROMs developed during the production process were duplicated (10,000 copies of each), packaged, and shipped along with the VPFVIEW software and user documentation to government distribution points in the United States, the United Kingdom, Canada, and Australia (see Appendix A).

The steps involved in database construction included scheduling, hardware assessment and acquisition, hardware and software configuration, source frosted acetate separate reproduction, source map preparation, digitizing/scanning, basic data processing, attribute assignment, edge matching, tiling, conversion to VPF, CD–ROM premastering and mastering, and packaging. The standard procedures for production were established during the prototyping phase and were documented in SOPs; the SOPs were updated and improved continuously during database production. Application routines written in the ARC/INFO Macro Language (AML) were extensively used in production to help reduce the processing time and standardize the processing procedures. The use of AMLs and the development of additional AMLs during the production period resulted in a three-fold increase in production efficiency during the twenty months of production.

1.4.2 Quality Assurance

A comprehensive quality assurance program was strictly adhered to during each process in DCW production to ensure the highest quality in the product. The quality assurance activities covered four areas: management activities in support of effective overall quality assurance for the project, software development, database development, and CD–ROM premastering and mastering. The first area was a pivotal component of the DCW project infrastructure; it controlled the inputs and outputs of the product development process and ensured the quality of the final integrated project deliverables. The other three areas were concerned with placing controls on specific product development activities. The primary focus of the quality assurance program overall was on the activities connected with database development, since this portion of the project was the most complex and labor intensive.

1.4.3 Operation Desert Shield/Desert Storm

While the DCW was under development, DMA requested that ESRI provide GIS database development support for Operation Desert Shield/Desert Storm. A great many technical resources and a great deal of effort were required to complete the digital data automation of the requested geographic areas within the Kuwait theater of operations within the given time frame. The urgent requirements of Desert Shield/Desert Storm necessitated special handling and tasking procedures and associated complex shifts in the DCW development staff. These special procedures were implemented in a timely and cost-effective manner, and urgent military and intelligence requirements were successfully met

1.5 Phase III—VSM and DNC Production

Prototyping for two additional DMA products, the VSM and the DNC products, is under way. This work is designed to meet the growing demand for military GIS analysis using VPF data. Each of these products represents a new chapter in the extension of VPF, which will be the standard format for all future DMA digital vector databases.

1.5.1 The VSM Project

VSM provides generic topographic data for a variety of U.S. Army and GIS intelligence applications in two scales referred to as medium and high resolution. The first VSM prototype will consist of two VPF databases automated from a 1:50,000 topographic line map of Killeen, Texas, and a Joint Operations Graphic (JOG) of the Waco–Killeen area at the scale of

1:250,000. After the database is automated in ARC/INFO, it will be translated from ARC/INFO to VPF. Additional prototypes are planned. As with the DCW product, VSM data will be delivered to DMA on CD–ROM. VSM will use the Feature Attribute Coding Catalog (FACC) coding scheme.

1.5.2 The DNC Project

In a second application of the VPF standard, a navigational database prototype also coded in FACC and formatted in VPF will be produced. The DNC project is a pilot program that will provide the U.S. Navy and U.S. Coast Guard with a digital geographic database prototype on CD–ROM that is capable of supporting ocean surface navigation. The DNC prototype database, which will range in scale from 1:20,000 to 1:500,000, is being populated with the feature content of eleven National Ocean Service (NOS) nautical charts from the Norfolk, Virginia and New York City harbors. The prototype database will contain approximately fourteen data layers, including port facilities, aids to navigation, limits, obstructions, and hydrography.

In the future, ship navigation requirements may be met through VPF databases published on CD–ROM instead of through traditional paper charts. If so, significant onboard space savings will be realized. More important, since spatial navigation systems built from VPF digital data will be able to undergo more frequent updates than paper charts, it will be possible to provide better descriptions of naval hazards to mariners, improving the safety of marine navigation.

1.6 Acknowledgments

The DCW is the culmination of vision, talent, and dedication on the part of many people (Appendix D). The contributions of all those who participated in the project, both directly and indirectly, are gratefully acknowledged.

Chapter 2. Phase I—Design and Prototyping

2.1 Chapter Overview

This chapter describes the objectives and characteristics of each prototype, the special studies conducted to determine the best solution for specific design problems, the development of vector product format, and the development of VPFVIEW.

Acronyms are defined in Appendix E.

2.2 Prototype Development

2.2.1 Prototype 1

2.2.1.1 Objectives

The objectives of Prototype 1 were to create a conceptual design for and to provide a preliminary demonstration of the content of the DCW database and the capability of the application software. Since one objective was to demonstrate the conceptual design, the prototype consisted of very preliminary user-oriented menus and a minimum amount of data. After being developed, Prototype 1 was sent to the DCW participants for evaluation and comments.

Prototype 1 was completed in December 1989 within eighty-three days after award of contract. In November 1989, the Project Requirements Review was held to set objectives for the project and the prototypes. Prototype 1 was developed in such a limited period of time that it was unable to benefit from the results of the subsequent special studies and standards development.

2.2.1.2 Design and Implementation

The two main issues addressed with the development of Prototype 1 were database content and the conceptual design of the application software.

Database Content and Design

The database design for Prototype 1 was topologically structured and reflected the DCW product requirement for layered thematic data sets. Database design began with an analysis of the two source maps, ONC G-18 and hydrographic chart BA-2693 from Harwich, U.K. The data layers in the design were grouped into six general themes: cultural, road network, hydrographic (i.e., drainage network), elevation, and marginalia (the last of these was not topologically structured). The database included all four ARC/INFO feature types (points, lines, polygons, and networks).

The database was topologically structured; that is, the spatial information was treated such that all areal space was accounted for in a mathematically rigorous fashion. A naming convention was used for the data layers that indicated both the general theme for the layer and the feature type contained in the layer. A coding structure was also developed for the types of features in each layer. A data dictionary reflecting all design decisions was developed to guide Prototype 1 database construction and attribute assignment.

Database Automation

The Prototype 1 database was manually digitized. ESRI's ARC/INFO software was used to process the digitized features and assign the associated attributes. The database was developed strictly in accordance with the specifications of the data dictionary. For this prototype, the data automated represented a small portion of both source maps.

Application Software Functions and Capabilities

The application software provided to reviewers to evaluate Prototype 1 was based on the PC ARC/INFO software. The application was written with the Simple Macro Language (SML) programming language. The application provided the user with a menu structure for performing queries and displays. Users could access the operating system, select features, prepare reports, and archive data.

The VPFVIEW software later developed through subsequent prototypes for the DCW is not ARC/INFO based and was written in C. PC ARC/INFO was used for Prototype 1, only because it provided ready-made display and query capabilities and could be used to rapidly mock up the conceptual design and the look and feel of the software ESRI envisioned for the final product.

The Prototype 1 software capabilities were as follows: the user could select only the data automated into the prototype database, and no methods for delimiting specific points or areas within that database were implemented. The only functional option on the Graphic Report menu was the one that enabled the user to draw to screen. For the Text Report function, the functions implemented were those that enabled the user to save to disk, display reports to the screen, and send a report to the printer. The Archive functions were implemented that allowed the user to save and restore data requests generated from earlier selections (the Save and Restore Feature Selection List options).

Thus, the software implemented for Prototype 1 demonstrated the design concept and the potential functions and capabilities the later software would have, although many of the menu options available in the final DCW product were not yet implemented.

Deliverables and submittals for Prototypes 1 to 4 as well as for all other DCW activities are listed in Appendix F.

2.2.2 Prototype 2

2.2.2.1 Objectives

The objective of Prototype 2 was to implement the concepts presented in Prototype 1 and to incorporate the feedback generated by the evaluation of Prototype 1. The application software

was coded in C, and the study area was expanded to include a larger geographic area. This prototype served to further demonstrate the conceptual design of the DCW product. It was delivered in April 1990; a January conference, the Design Concept Review, provided DCW participants with an opportunity to discuss Prototype 1 and to understand ESRI's plans for Prototype 2 development.

2.2.2.2 Design and Implementation

As was true for Prototype 1, the principal issues addressed within Prototype 2 were database content and the conceptual design of the applications software.

Database Content and Design

To demonstrate the functions and capabilities of Prototype 2, new data sets were automated. For most of the prototype areas, partial sheets were automated. Table 1 lists all sample areas and source scales for each. These varied sources were automated to ensure that the DCW design was flexible enough to accept data from diverse sources that contained different themes and were created at different scales.

Table 1. Prototype 2 Sample Areas

Source Map or Chart	Location	Source Scale
ONC G-18	California/Nevada	1:1,000,000
BA 2693	Harwich, England	1:25,000
NOS 12222	Hampton Roads, Virginia	1:40,000
NOS 12245	Hampton Roads, Virginia	1:20,000
Topographic map	Killeen, Texas	1:50,000

Some aspects of the Prototype 2 database design were reworked, and the data inclusion criteria were modified, as the result of Prototype 1 feedback. As for Prototype 1, all data from all sources were grouped in layers, and layers were grouped in themes.

The new data layers added to the Prototype 2 database included Political Boundaries/ Administrative, Miscellaneous Culture, Utilities, Air Transportation, Navigation Demarcation, Bathymetry, and Isogonic Lines. In addition, for all data sets associated with selected geographic layers, an annotation layer was automated.

Data Structure and Symbology

Like the data for Prototype 1, the data for Prototype 2 were encoded in the ARC/INFO data structure. The study that led to the development of VPF (the data structure used for the final product) was initiated after Prototype 2 was released and applied to the DCW data sets beginning with Prototype 3. VPF will be discussed in greater detail later.

Similarly, the symbology utilized for Prototype 2 did not take into account results from the symbology study (see Section 2.3.6), since the symbology study was undertaken while Prototype 2 was being developed.

Database Automation

Starting with Prototype 2, the feasibility of using scanning techniques to capture data was explored. Benchmarks were designed and implemented on a variety of different scanning hardware and vectorization software configurations to test the cartographic accuracy of the results. The principal determining factor for scanner/vectorization software selection was the quality of linework exiting the vectorization processor. Analysis during this time period showed that vectorization algorithms which first calculated a "casing" around linework and then calculated a centerline from the casing were superior to so-called "pealing" algorithms. Additional analysis regarding scanner resolution indicated that to achieve the DCW line accuracy specification, scanners with 400 Dots Per Inch (DPI) to 500 DPI provided sufficient scanning resolution. No DCW data were scanned at a higher resolution than 500 DPI.

For Prototype 2, the elevation contours in ONC G-18 were selected and scanned; all other types of data were digitized manually. The scanned data were converted from raster data format to vector data format by using vectorization software. ARC/INFO utilities were then applied to transfer the vectorized data from DXF format to ARC/INFO vector data format. Data processing and editing were then performed in the ARC/INFO environment. For the manually digitized data, ARC/INFO software was used to support the digitizing process and to assign feature attributes.

Application Software Concept

The user interface was considered key to the success of the application software. Therefore, as for Prototype 1, the user interface for Prototype 2 was intended to closely resemble the interface to be used for the final DCW product. The focus of software development continued to be a "core" subset of the final software's capabilities, such as its query/selection and graphic display capabilities.

Application Software Design and Development

Many concepts designed but not yet implemented in Prototype 1 were implemented in Prototype 2. In addition, some new capabilities were designed and included in Prototype 2 in response to participant evaluations of Prototype 1. These included a "mouse" interface, a zoom capability, and more straightforward ways to move between menus.

Beginning with Prototype 2, all software was designed and coded in C. This was a major difference between Prototypes 1 and 2; since Prototype 1 was based on PC ARC/INFO and the application software was coded by using SML, none of the Prototype 1 code was utilized in Prototype 2.

An on-line data dictionary was designed and implemented for Prototype 2. It was intended to provide the user with on-line information about the DCW project and the database structure, layer and feature content, and code correspondence to the DIGEST FACC codes or other coding systems. In later prototypes, the on-line data dictionary was expanded to allow the user to review the contents of the DCW product or to query specific attribute code values for features of interest. For example, for the final product, the data dictionary may be queried for attribute code values. For Prototype 2, a query of the data dictionary resulted only in a listing of an ASCII file containing the physical design of a specific layer.

Also in Prototype 2, a code correspondence option was implemented that displayed a cross-reference between the ONC symbol codes and the DIGEST FACC codes and DCW codes.

A gazetteer function (place name index) was implemented in Prototype 2 that allowed the user to select areas of interest by name. The user entered the desired feature name in a fill-in box, and the software responded with a list of the place names that began with the letters specified.

In all, the core commands that were not functional in Prototype 1 were successfully implemented in Prototype 2. However, peripheral commands that appeared in the final product were not yet implemented in this prototype, including Text Report, Select by Box, Select by Latitude/Longitude, and Select by Pointing.

2.2.2.3 Summary

Prototype 2 exceeded its original design objectives, and significant progress was made toward a final database and software design. For the database, the data inclusion criteria were modified, and the database was expanded to include themes and layers that were not present in Prototype 1. For the application software, the functions and capabilities of Prototype 2 surpassed those of Prototype 1 in terms of "look and feel," query/selection capabilities, and graphic display capabilities.

The aspects of Prototype 2 that were not representative of the final DCW product included data structure and symbology. The data for Prototype 2 were still in ARC/INFO format, whereas the data for the final DCW product would be in VPF. The symbology used for Prototype 2 was also part of an ARC/INFO utility. Symbology designed specifically for the DCW product was implemented in the next prototype. It should also be noted that Prototype 2 was developed without the full benefit of the special studies and standards that were being developed concurrently.

2.2.3 Prototype 3

2.2.3.1 Objectives

The objectives for Prototype 3 were to finalize the DCW database content and to fully implement all software functions. The extent of data to be automated was further expanded, and production procedures for database development were established. The Prototype 3 database was the first to be delivered on CD-ROM, and it was the first database to be prepared in vector product format. However, the VPF standard continued to evolve beyond this point.

Prototype 3 was delivered in August 1990. Review comments on Prototype 2 and ESRI's plans for Prototype 3 development were discussed at the Preliminary Design Review in May.

2.2.3.2 Design and Implementation

Database Content

Large sample areas were included in the Prototype 3 database. For most of the prototype areas, complete sheets were automated. Table 2 lists all sample areas and source scales for each. The DMA's Digital Air Facilities Information File (DAFIF) was used to extract airport information for the aeronautical layer. The database for Prototype 3 incorporated data from

varied sources and at different scales to show that the VPF data structure was flexible enough to accept data from sources other than the ONCs.

Table 2. Prototype 3 Sample Areas

Source Map or Chart	Location	Source Scale
ONC G-18	California/Nevada	1:1,000,000
ONC E-18	Quebec, Canada	1:1,000,000
ONC N-13	Northern Territory, Australia	1:1,000,000
JNC 120	Antarctica	1:2,000,000
BA 2052	Harwich, England	1:50,000
NOS 12245	Hampton Roads, Virginia	1:20,000
Topographic map	Killeen, Texas	1:50,000

Nine new layers were added to the DCW design, one layer was deleted, and minor design changes were made to other layers.

All data sets were automated in ARC/INFO coverages. A prototype data format converter was designed and developed in C to convert data in ARC/INFO data format to VPF.

Database Design and Vector Product Format

The Prototype 3 database was different from the previous prototypes in that the data structure used was vector product format. Throughout the Prototype 3 and 4 timeframe, VPF continued to evolve based on data handling experiences from the two prototypes.

Vector product format can support spatial query, display, and modeling directly (without conversion to another format). The VPF data model is flexible in that it provides a data structure that can be tailored to particular needs and applications. The study that culminated in the development of VPF was initiated after Prototype 2 and was applied to the Prototype 3 data sets. VPF is discussed further in Section 2.4.

Like the databases for Prototypes 1 and 2, the database for Prototype 3 was arranged in layers that contained specific features or feature groups and associated attributes. Each thematic layer was stored as a single coverage. The features in the thematic layers were defined by attributes and attribute-value code combinations.

Production Procedures

During the Prototype 3 period, production procedures continued to be developed. These procedures were documented in SOPs that were held in a document nearly 300 pages long.

Symbology

The other important difference between Prototype 3 and the two previous prototypes was that the symbols used in Prototype 3 were designed specifically for the DCW product. Prototype 3 also provided the user with limited cartographic design and symbology options. The symbol sets designed for Prototype 3 included the drawing primitives supplied with the C graphic

library (simple lines and polygons), the ASCII character set (points), a minimal set of complex line algorithms, and a preliminary library of marker symbols (points).

Although the actual symbol design, color selection, line styles, area patterns, and point symbols continued to evolve, the Prototype 3 symbology reflected the efforts described in the initial symbolization study, which was undertaken to evaluate considerations of cartographic design, feature symbology, and the capabilities of the software to present a more typical map display.

Application Software Design and Implementation

As with the previous two prototypes, efforts were made with Prototype 3 to develop a menu structure that would match the final DCW product as closely as possible, even though some of the menu commands were not implemented.

For Prototype 3, the development of software functionality included the development of display functionality (and the associated symbology), spatial and attribute query functionality, indexing capabilities, and gazetteer/functionality. Participant comments on Prototype 2 were carefully evaluated and implemented in Prototype 3.

Several new user-oriented functions were added, including a high-level "screen draw" command, adaptive menus, a map distance-measuring function, a map scale function, projection capabilities, and status windows.

Software graphic display capabilities were modified in Prototype 3 so that features could be selectively added to a display after the main part of the display had already been drawn on the screen.

CD–ROM Design and Implementation

Since the final DCW product was to be distributed on the CD–ROM media, production steps regarding the premastering and mastering of CD–ROMs for data storage were also conducted during this prototype. In addition to the DCW, database-supporting data such as indexes, quality reports, and gazetteer and data dictionary information were also stored on the CD–ROM.

The CD–ROM manufacturing task involved the transferring of digital source data from magnetic media to the CD–ROM. The task had two primary phases: premastering and mastering. Premastering involved testing data integrity at a number of key steps in the process. Mastering involved producing master "molds" and monitoring the physical characteristics of the discs. During CD–ROM premastering for Prototype 3, ESRI successfully organized the database into four libraries that contained all data in the geographic sample areas.

2.2.4 Prototype 4

2.2.4.1 Objectives

Prototype 4, which was delivered in December 1990, fully implemented the database revisions and the new application software functions based on Prototype 3 reviewer comments. Prototype 3 and plans for Prototype 4 were discussed at the Project Detail Design Review in

August. This prototype served as a production "dry-run," and a thorough set of SOPs for the full-scale production process was developed as the prototype was produced. From this prototype, the prototype reviewers received a very close mockup of the appearance and operation of the final DCW product.

2.2.4.2 Design and Implementation

Prototype 4 represented revisions in database content and accuracy; the implementation of new application software functions and capabilities; the further development of VPF; the development of a software users manual; the development of final symbology; the implementation of a database tiling structure; the finalization of production procedures; and the establishment of database quality assurance procedures.

Database Content

Data from four ONCs of Western Europe made up the Prototype 4 database: ONC E-1, ONC F-1, ONC G-1, and ONC G-2. Five new thematic layers were added to the DCW design: Vegetation, Landmarks, Transportation Structure, Hypsography Supplemental, and Drainage Supplemental.

The Vegetation layer contained those areas that were labeled "vegetation" or "clearing" on the ONCs. The vegetation data were represented as polygons. The Landmarks layer contained point and polygon features that were captured on the ONCs because of their visual prominence. The Transportation Structure layer contained a variety of transportation features that were added to the DCW design to supplement the Road and Railroad layers. The features in this new layer included bridges, tunnels, causeways, ferries, fords, and so forth; they were represented by points and polygons.

The Hypsography Supplemental layer was introduced to capture small contour areas as points (those with a circumference less than 0.12 inch). These small polygons were not captured in previous prototypes because they could not be captured as polygons. In this layer, they were captured and converted to elevation points.

In the new Drainage Supplemental layer, as in the Hypsography Supplemental layer, small polygons in the Drainage layer (those with a circumference less than 0.12 inch) were captured and converted to points. In the Drainage Supplemental layer, these small polygons mainly represent small lakes and small islands in inland lakes.

Prototype 4 also introduced a new approach to the representation of elevation data. The point and line coverages within the Hypsography layer remained largely the same, but the polygon coverage was revised to contain six elevation zones. Zones were introduced because they reflected distinctions with respect to a number of important natural and cultural factors, including vegetation patterns, agricultural land use, population distribution, equipment performance, and human health and comfort.

Modifications to the VPF Military Standard within Prototype 4

Three primary goals were set for VPF data structure: to support spatial and thematic display, query, and modeling; to support tiling and the sheetless assembly of tiles; and to support work with a wide range of media, including CD-ROM, tape, and hard disc. Significant effort was

applied to the development of this data structure and the related military standard (see Section 2.4).

The implementation of VPF in Prototype 3 signaled the beginning of the standardization of the DCW data storage format. The VPF military standard was revised to explain VPF in terms of a five-level hierarchy that included the product specification, a data model, the data structures, encapsulation, and data syntax. The revised standard proved its flexibility through its successful application to Prototype 4. The ARC/INFO-to-DCW converter initially created to support Prototype 3 was modified to convert Prototype 4 ARC/INFO data into VPF.

Applications Software Functions

The software capabilities provided by Prototype 4 were representative of all user-oriented functions of the final DCW software. Subsequent modifications to the software focused on internal engineering, performance enhancement, and extension of the software to read any VPF database. (Because of this extension, the name of the software was changed from "DCW Applications Software" to "VPFVIEW.") Additions and refinements suggested by participants after reviewing Prototype 3 were carefully considered, and many were incorporated in the final software design. New functions and capabilities provided by Prototype 4 were as follows:

- Zoom—Users could zoom in and out of the DCW database. The zoom capability could also be used to move from the DCW Browse map, which was the first data set visible to the user, to the more detailed DCW data set, and vice versa.

- Help—Users could access a Help option. Help was available at both the main and pulldown menu levels.

- Generated Graphics—Users could generate two types of graphics: (1) a latitude/longitude grid and (2) a scale bar.

- Status Windows—Status Windows were provided to show the software operations (e.g., drawing, initialization).

- Select by Pointing, Latitude/Longitude, or Place Name—Users could select an area of interest by pointing the cursor at any geographic location on the Browse map. Users could also specify an area of interest by entering latitude/longitude or place name.

- Text Report—Users could produce three types of text reports. The Feature Location List and the Area Content Summary contained attribute information for selected features within a specific study area. The Feature Location List provided a report of the location of these attributes, while the Area Content Summary provided a report of feature type and count. The international Feature Attribute Coding Catalogue (FACC) correspondence report contained a table comparing the DCW and FACC coding schemes. (FACC is the coding structure for the DIGEST standard.)

- Spatial Query—Users could identify the attribute characteristics of displayed features by pointing the cursor at a geographic location on the screen.

- PostScript interface—Users could generate a PostScript plot file of the selected features by using the Hardcopy option on the Graphics menu.

Browse Map

The most obvious change to software functionality was the design and implementation of a Browse map for Prototype 4. It replaced the index map provided with the previous prototype. The Browse map was a basemap that was designed to accomplish four objectives: (1) to serve as a start-up screen for the DCW; (2) to provide an index map for the user; (3) to allow the display of metadata; and (4) to provide a bounding geographic area context to support zoom-outs. In operating the Browse map, the user could:

- Select a specific area of the DCW to examine in greater detail.
- Manipulate the zoom function to move from the Browse map data set into the DCW data set and back out again.
- Retrieve metadata (e.g., compilation dates, data volumes, and data availability) from the DCW data set.

Development of the DCW Applications Software Users Manual

A software users manual was developed for use with Prototype 4. The manual described the DCW applications software and explained its use. This document also described system requirements and provided a high-level design description. The manual enabled the user to operate the DCW display software and to understand many aspects of system design. The users manual ultimately served as a mock-up for the "VPFVIEW Users Manual for the DCW," which was distributed with the DCW in 1992.

Symbology Development

As with Prototype 3, a full default symbol set was provided for this prototype, which could be altered, added to, or completely replaced by the user. However, several changes were made to the design and implementation of the Prototype 4 symbology.

Text. The main objective of changing the symbology used for Prototype 4 was to reduce clutter (crowding), especially for text. Therefore, for Prototype 4 the text was scaled directly in proportion to its relative size in the source ONC. The size of the text was also related to the scale (zoom factor) selected by the user. Text, if selected, was displayed regardless of display scale (the display of text was not disabled at small scale). To avoid clutter at small scale, text appeared as a row of pixels. As the user operated the zoom function to increase the display scale, the size of the text increased proportionally. Text became increasingly legible with each successive zoom.

Another design change for Prototype 4 was that the user was able to select the color used for the text (by overriding the default text color). Providing this functionality was essential to keep text visible yet give the user a free choice of color for areas.

Points. Several additions were made to the feature symbology set in Prototype 4; there was a digital version of almost every point symbol in the ONC source, even though some of them were redesigned later in the final DCW product.

Lines. Primarily because of the limits of screen resolution, line symbology remained less than ideal for Prototype 4. However, the quality of the "dot" and "dash" line patterns generated by the software was substantially better than in Prototype 3. Line symbology could be optimized through the selection of line color and thickness.

Areas. One of the most important improvements to Prototype 4 feature symbology was a new approach to area fill. Area fill for Prototype 4 was provided exclusively by color, and the color could be controlled by the user through the "pixel mixing" technique presented at the Project Detail Design Review. The user could control color through the menu by selecting a color for each of the four pixels that make up a given color. The objective of using color fill was to replace the cross-hatching and other pattern area fills used in Prototype 3, which produced clutter and detracted from the readability of the display.

Database Tiling

The tiling or database partitioning scheme for the DCW product was designed and implemented in Prototype 4. The tiling scheme is largely invisible to the user, but it is of tremendous interest to the database designer because of its role in database management and its impact upon system performance. The tiling scheme (tile size and the number of tiles) implemented was evaluated for both design effectiveness and effectiveness of performance.

Two tiling schemes were proposed and presented for evaluation: a 5-by-5-degree data partition and a 3-by-3-degree data partition. For Prototype 4, features could be drawn to screen by using either partition.

Within the tiling design study that preceded Prototype 4, two fundamentally different tiling schemes were considered: adaptive and fixed. Because of its ability to manage large variations in data density, an adaptive rather than a fixed tiling scheme was initially believed to be the best. However, as the DCW evolved through the prototyping process, it became clear that the value of managing variations in data density would have to be weighed against the disadvantages of any adaptive tiling scheme for other aspects of the DCW product, particularly the DCW production process and the ability to overlay the DCW database with future VPF products.

By the time Prototype 3 was released, a fixed tiling scheme was recommended because fixed tiling provided an effective data range, allowed database production to proceed independent of conversion to DCW format, and provided a predictable framework for other efforts, including geographic organization.

The size of the tiles was decided after the performance of Prototype 4 was thoroughly examined. At that time, ESRI considered the use of larger tiles (including 7.5 by 7.5 degrees and 10 by 10 degrees) to reduce the number of tiles and improve performance. However, because of the limitations imposed by software operating on a small machine (286 or 386), a 5-by-5-degree tiling scheme was eventually chosen for the final DCW.

Database Automation

The most obvious improvement in database automation for Prototype 4 was the large-scale use of scanning; scanning was faster than manual techniques for capturing linear features and

features bounded by polygons. In some situations, scanning was also used to capture point features. Database automation for DCW production is described in more detail in Chapter 3.

Edge Matching

Prototype 4 was the first prototype to contain adjacent ONC sheets and therefore represented the first opportunity to employ and examine edge matching procedures for the DCW. Edge matching issues are those connected with locational accuracy, sheet overlap, and attribute coding.

Locational accuracy is an issue because some linear features did not match across map sheet boundaries. In these cases, the linear features from the less accurate ONC sheets were matched to those in the more accurate sheets.

Overlap existed between adjacent ONC sheets. The features within the overlap area did not always match because different sheets had different compilation dates. The solution was to use only the overlap area from the more recent of the two sheets as a data source.

Because of different compilation dates, attribute coding often changed across module boundaries. When this occurred with linear features, a pseudonode was placed on the module boundary and the linear features were coded separately. When attribution of polygonal features changed at map sheet boundaries, the polygon was split along the module border, and the faces, as well as their composite edges, were coded separately.

Development of Standard Operating Procedures

One of the main objectives of developing the DCW was to establish standard procedures for database development. Therefore, during Prototype 4, as production was planned, detailed SOPs were written. The Prototype 4 SOPs developed in this manner were not final, since some of the production procedures were modified during the production process; however, the Prototype 4 SOPs served as the foundation for the final production SOPs.

DCW Product Specification Development

The draft version of the DCW product specification was developed for this prototype. The product specification was written to provide a fully detailed description of the DCW. Accordingly, the specification includes both explanations of the format of the various types of VPF tables used for the database and detailed lists of the content of each database layer. The final, approved version of the specification (which is available at the address listed in Appendix B) also includes DCW-to-FACC/FACS code conversion tables.

The final, approved version of the specification represents the seventh iteration of the specification. Each version reflected expansions in the database and also the gradual development of VPF. The first version was released with Prototype 2; at that time the database was in the earliest stages of development, and the specification merely represented an outline of intended product content. The second (interim) version of the specification was released concurrent with Prototype 3, and the fourth (draft) version of the specification was released concurrent with Prototype 4. Each of these and the later versions of the specification reflected the gradually expanding database and more results of the studies that were being completed at that time.

2.2.4.3 Summary

Prototype 4 represented fully functional DCW application software and a supporting database. As the final prototype, the standards and procedures developed for this prototype established the guidelines for the subsequent production of the full-scale DCW. As a result, some important issues concerning database content and application software were addressed in Prototype 4, including database content and data accuracy for small polygon features. More advanced software functionalities were implemented, including zoom, help, generated graphics, and a Browse map. The results of some special studies were also implemented in this prototype, including studies made to evaluate symbology and tiling structure. Quality assurance activities established for production procedures were effectively implemented in this prototype. Most important, the VPF concept was redesigned and implemented within this prototype.

Prototype 4 was the last prototype and signaled the beginning of full-scale production. The implementation of application software was finalized and the future focus of software was on software engineering and the associated preparation of a software product (versus a prototype). At the end of this prototype phase, resources, procedures, quality control, and facilities were all ready for full-scale DCW production.

2.3 Special Studies

2.3.1 Aeronautical Information Study

The aeronautical information study was one of a series of special studies conducted during the DCW project. The main objectives of the aeronautical information study for the DCW were to determine what types of aeronautical information should be included in the DCW and to recommend a methodology for the capture of aeronautical information. (The aeronautical information on the ONCs and JNCs included navigation aids, airfields, obstructions, and flight control zone information.) A secondary objective of this study was to determine whether aeronautical information should be held in a separate limited distribution file that Department of Defense users could overlay on the DCW product.

The results of the aeronautical information study were presented in initial and final reports. The initial report described the methodology used to select, portray, and compile the aeronautical information in the ONC series. The types of information in the ONCs were categorized and described. The results of an assessment of user needs for aeronautical information in the DCW were described, guidelines for data evaluation were established, recommendations concerning types of aeronautical information to be included in the DCW were made, and sources for the aeronautical information to be included in the DCW were recommended. The initial study was finished in February 1990; it was distributed to DMA and DCW participants for review. Comments from the evaluation were considered for incorporation in the final study.

The final study made further recommendations concerning the inclusion of aeronautical information in the DCW. Its recommendations were implemented in Prototypes 3 and 4. The final study also made recommendations concerning the query and display of aeronautical information.

As a result of these studies and an assessment of user needs, it became clear that the DCW should not be used for flight planning or actual aircraft operation. Therefore, the information on the ONCs concerning air traffic control zones and vertical obstructions was not included in the final database. However, the location of airports was retained. The data source for airports in the former Eastern Bloc nations was the ONCs. The data source for airports in the free world was the DMA Digital Aeronautical Flight Information File. A small subset of the DAFIF attributes was also entered in the database.

2.3.2 Elevation Data Study

2.3.2.1 Objectives

The elevation data study was undertaken with the following objectives:

- To determine the categories of ONC elevation data needed in the DCW.
- To determine what form the elevation data should take, including the display of the digital elevation data to the user.
- To determine whether other sources of elevation data, such as Digital Terrain Elevation Data (DTED), could be used, and if so, which.

2.3.2.2 Elevation Data Present on the ONCs

The elevation data study entailed understanding the methods used to acquire and depict elevation data in the ONC series. A visit to DMAAC in St. Louis was thus made in order to discuss ONC chart creation with DMAAC production staff.

The elevation data for the ONCs were acquired from large-scale maps, which were photographically reduced and placed edge to edge, creating a mosaic that fit a computer-generated graticule; the graticule was projected and scaled to match the ONC being developed. This compilation process resulted in the grid controlling the orientation of the manual pasteup mosaics of selected elevation source data, and lessened the control problems typically associated with manual pasteup procedures. Adjustments were made if they were necessary to create a good "match" between the source documents and the ONC maps. These compilation procedures maintained the positional relationships between the elevation data (contours and spot elevations) and other ONC data.

The most common contour intervals on the ONC charts were 1,000 feet (the basic contour interval); 2,000 feet in mountainous areas; and 500 feet in flat areas, especially coastal areas. Intermediate 250- or 200-foot contour intervals were also used. The elevation data were enhanced by tinting and shading of the terrain relief. Point elevation data were also present on the ONCs.

A significant number of charts were devoid of elevation data. Contour coverage was less than 100 percent on 173 charts, and some of these did not have elevation data at all.

2.3.2.3 Assessment of User Needs for Elevation Data

As part of the elevation data study, user needs were assessed. Questionnaires were distributed to DCW participants, and the best way to process and store elevation data was then discussed at the Design Concept Review in January 1990. Most of the respondents to the questionnaire felt that elevation data were most useful if presented as an arrayed (i.e., grid, or raster) data set. DTED format was recommended especially highly; existing software is capable of supporting both graphic displays and such analyses as intervisibility studies, line-of-sight calculations, terrain masking, mobility analyses, and so forth.

However, in spite of the desire expressed by participants for arrayed elevation data, participants also stressed that an arrayed elevation database must correlate exactly with the feature data on the ONC charts from which the majority of the DCW data were to be extracted (which would entail a review of the positions of all feature data). Since available array elevation data sources were not correlated with ONC source documents, correlation of arrayed data with feature data clearly represented a significant upscope for the DCW project. Therefore, after the Design Concept Review (DCR), the scope of the elevation study was directed to be expanded to include a preliminary investigation of the feasibility of producing an arrayed data set from both the ONCs themselves and from other data sources.

2.3.2.4 Evaluation of Feasibility of Developing Array Data from ONCs

To evaluate the feasibility of developing array elevation data from the ONCs, a feasibility study was conducted to do the following:

- Define a sample array data area by latitude and longitude and recommend the proper horizontal and vertical intervals for the array.
- Evaluate the impact of the currently recommended tile structure on the elevation array.
- Recommend a file structure for the proposed array data.
- Determine how to code the elevation values.
- Estimate the amount of the data storage space necessary for array data developed for the entire database.

2.3.2.5 Recommendations

The recommendations concerning the inclusion and portrayal of elevation data for the DCW were as follows. ONC elevation data were recommended as the source data for the DCW (it was recommended that the DCW not make use of any elevation data external to the ONCs). The data were to include all 1,000-foot contour data; all supplemental or intermediate ONC contour data, including form lines and approximate contours; and all ONC spot elevations (land and water). It was further recommended that contour bands/polygons be prepared for all 1,000-foot contours and that ONC contour anomalies be given special handling.

The handling recommended for contour anomalies was to use polygons to define all areas where contours either were not present or did not conform to standard definitions; to use polygons for closure of contours; and to use meridians and parallels approximating the ONC sheet edges both to connect and to close contours and contour bands. Contour connectors were to be appropriately attributed.

The study also indicated that contours, contour bands (polygons), and spot elevation should be implemented in the DCW product in accordance with the VPF structure and tiled in accordance with DCW tiling study recommendations. The DCW elevation data were thus not presented in an arrayed form primarily due to the necessity for a significant project upscope if this was attempted.

2.3.3 Tile Design Study

2.3.3.1 Introduction

Because of equipment limitations, such as the availability of Random Access Memory (RAM) or software limits, a spatial database greater than a certain size becomes too large to manage as a single unit and must be partitioned into smaller units. The mechanism for breaking a large spatial database into smaller units is termed tiling, or partitioning. Because of the size of the DCW (about 1.7 gigabytes of digital data), a tiling scheme needed to be designed for it.

Two tiling schemes were considered for selection, adaptive and fixed. In an adaptive-tiling scheme, tile size varies according to data density (tiles are smaller where data are dense). Adaptive tiling is suited to spatial databases with great variations in data density. In a fixed-tiling scheme, the physical area of partition is set and the volume of data within it is allowed to vary.

The tile design study was undertaken to explore the best way to partition the DCW database. The results of the study were reported in initial, interim, and final reports. Data density varied greatly from one ONC sheet to another, and when the tiling study was begun, adaptive tiling was believed to be preferable to fixed tiling. It was believed that adaptive tiling would permit superior performance. However, as the DCW evolved, it became clear that the value of managing variations in density would have to be weighed against the disadvantages of adaptive tiling for production and for use of the DCW with other products that use fixed tiling (such as DTED). Fixed tiling also provided a consistent framework for other ongoing studies such as the geographic organization study.

By the time Prototype 4 was released, the recommendation for the tiling scheme had shifted from adaptive to fixed. Fixed tiling was implemented in Prototype 4 with two implementations of tiling sizes: 5 by 5 degrees and 3 by 3 degrees. Part of the evaluation of Prototype 4 involved determining the most advantageous tiling size.

It was indicated in the study that for a product with one dominating constraint, the tiling scheme selected must optimize for that constraint. However, a general-purpose database like the DCW has no dominating constraint and must therefore utilize a tiling scheme that is satisfactory from the standpoint of all constraints on the database. Six special requirements for the DCW tiling scheme were identified in the study.

- The selected scheme must cover the entire surface of the globe.
- It must be possible to implement the scheme effectively; the tiling scheme must be integral to the database, yet the implementation of the scheme must be unaffected by (and devoid of impact on) the sequence of database production.
- The tiling scheme must conform to VPF.
- The tiling scheme must be usable with both existing and future products.
- The tiling scheme must allow whole tiles to be placed on a single CD-ROM.
- The tiling scheme must be compatible with the indexing scheme used for the DCW.

2.3.3.2 Evaluation of Adaptive and Fixed Tiling

Adaptive Tiling

To implement adaptive tiling, one needs to estimate the volume of data for a certain map sheet to see if the volume exceeds a certain threshold. If so, partitioning is required. If partitioning is done, the data volume for each resulting quadrant of the map sheet is estimated to see if the data volume of any quadrant still exceeds the threshold. If so, that quadrant must be partitioned again. The process continues until no quadrant (tile) exceeds the maximum allowable data volume. The final step is to assemble the map sheet with adjacent sheets.

The results of the study indicated that adaptive tiling is highly sensitive to data content and that, through the data volume estimate procedure, it is closely coupled to changes in data content and representation. In addition, the final global tiling scheme cannot be determined until the last map sheet is automated and the final partition is produced. This characteristic represented the biggest obstacle to developing a scheme for the geographic organization, or allocation of tiles, to the CD-ROMs. In addition, by adopting an adaptive tiling scheme, the large effort associated with the production process of tiling would have needed to be delayed until all automation was complete. The DCW production schedule would not support this constraint.

Fixed Tiling

Fixed tiling was the other option for tiling the DCW database. Fixed tiling is the opposite of adaptive tiling in that tile size is the same throughout an area. Furthermore, once defined, the size of fixed tiles remains the same throughout subsequent processing.

As with adaptive tiling, implementing fixed tiling requires both the development of partitioning procedures and the determination of the unit of measure to be used to define the partition. However, unlike the adaptive method, these determinations can be made *before* production. Systematic partitioning along a longitude-latitude grid is a common, well known form of spatial division, and this type of partitioning was used for the DCW database.

Once tile size is determined, fixed tiling, unlike adaptive tiling, does not require the evaluation of data content. A grid can be mathematically generated quickly and accurately for all or part of the globe. The tiling can begin as soon as the first layer within the map sheet is finished, and any map sheet can be automated and tiled immediately (without assessing the content of

incomplete tiles). This degree of independence between the tiling scheme and the production of data is advantageous, since the sequence of map sheet processing is not affected by the tiling procedure. Thus, by comparison with adaptive tiling, fixed tiling does not adversely affect the production process.

The tile design study indicated that it was important to determine tile size before implementing the tiling scheme. Determining a fixed tile size is a function not only of data content but also of the characteristics of the software and of the database storage media (CD–ROM, for the DCW database). The preliminary CD–ROM indexing studies discussed in Section 2.3.4 indicated that query response time was effectively linear for a given range of geographic extents, which correspond to a range of data content. This meant that within a certain range of geographic extents, query process times were linearly related to the number of features for a given feature type. The objective was to select a tile size that would allow data volumes to stay within the linear range. The two fixed tile sizes suggested were 3 by 3 degrees and 5 by 5 degrees. These two spatial extents corresponded closely to the lower and upper file size range limits reported in the indexing studies.

The final tile size selected was 5 by 5 degrees. The selection was based on the careful evaluation and determination of data volume, software functionality, the capabilities of secondary storage devices, production constraints, database maintenance, geographic organization, the potential incorporation of other products, and user needs.

2.3.3.3 Summary and Recommendations

The study report recommended fixed tiling as best suited to the DCW database. Fixed tiling was simple, stable, easy to understand and create, and could be implemented independent of database construction and maintenance. A decision to use fixed tiling also enabled other project activities, including the development of the geographic organization of the database, software functionality, and data structure, to proceed independently of the tiling process.

2.3.4 Indexing Studies

The DCW indexing studies were made to investigate methods to allow efficient DCW database queries, given the constraints of the hardware and software environment. (See Section 2.5.3 for a description of this environment.) The studies were initiated in July 1990 and implemented and modified in Prototypes 2 to 4.

2.3.4.1 Introduction

The objective of the indexing studies was to evaluate and propose methods for implementing database queries of four types: spatial queries, thematic queries, queries through the gazetteer (or place name index), and queries based on coverage. The indexing designs were adapted and modified through the evaluation of the prototypes according to the needs of the software and of VPF.

The original approach taken to the study was to use additional indexes to solve such problems as polygon shading. However, the indexing-only approach caused poor performance because it could not deal adequately with the complex interrelationship between VPF, the VPFVIEW software, the DCW data content, and the minimum hardware configuration. For example, VPF stated that polygon data must be implemented in four related files. Reading these four

files simultaneously for polygon shading was very slow. To reduce data access time, a special shading index was tested within Prototype 3 in which the necessary information for shading was collected in a single file. Unfortunately, this implementation violated a functional VPF requirement that there be no redundant data, so the index-only approach was abandoned.

To solve the performance problem, performance studies were then undertaken to examine all aspects of performance and to implement solutions using multiple techniques. Indexing was one of the techniques used to speed up data access times; others included hardware drivers, software techniques, and user query methods. The various techniques were implemented and evaluated in a cyclic process that included the implementation of the techniques currently thought best (optimization), testing, analysis, and refinement. The cyclic process was followed through three prototypes, beginning with Prototype 2.

Because VPF was constantly evolving, final solutions could not be developed until Prototype 4. Optimization work in Prototypes 2 and 3 concentrated instead upon the basic attributes of the hardware and software system components (the CD-ROM drive, the minimum hardware platform, the C programming language, and the software design). This performance analysis process ended in February 1991, with impressive improvement in some areas. The functionality requirements stated earlier (for spatial queries, thematic queries, etc.) were met by software functions implemented in VPFVIEW as follows:

- Spatial query: spatial query index
- Thematic query: theme and feature selection menus (thematic index)
- Gazetteer query: gazetteer index
- Query based on coverage: Browse map (coverage index)

As a summary, the indexing studies were initially limited to investigating indexing techniques for the CD-ROM data storage medium. The studies showed that optimizing the indexing techniques for the CD-ROM itself failed to address many of the complex issues that affected the interaction of the DCW software and database (i.e., performance). Therefore, the scope of the studies gradually expanded to include the effects on data access of other aspects of system design, including the demands of VPF, the functionality of the software, and the characteristics of the minimum configuration hardware. The CD-ROMs that represented the scope of the original studies were studied as an integral part of the hardware environment.

2.3.4.2 Methodology Used for Performance Testing

The analysis and test methodology had four steps: optimization, testing, analysis, and refinement. Optimization was the incorporation of performance improvements and indexing designs into the software. Testing was the process of implementing the optimized design into the system; it involved the measurement of many different aspects of the software and revealed any improvement due to preceding optimizations and indexes. Analysis was done during and after testing to detect improvement. Refinement represented the transformation of analysis into the improvement of the software, hardware, and data structures. These four steps represented the overall testing structure that was applied to Prototypes 2 to 4.

2.3.4.3 Test Results

Prototype 2 Results

Prototype 2 represented the first round of testing, and the prototype software and database were on a floppy disc, rather than CD–ROM. Therefore, a series of basic hypotheses about the functioning of the CD–ROM at the file level were defined and tested.

Optimization. Four proposed index structures were carefully sized so as to fit in RAM or on the hard disk. These four indexes were the gazetteer index, master disc spatial extent index, current CD spatial and thematic index, and master thematic index. The gazetteer index was a simple list showing place name and latitude/longitude. The gazetteer function skipped the spatial index and read the gazetteer index directly to print out name and location as text. The master disc spatial extent index was a list of the contents of each disc. The current CD spatial and thematic index was a summary of the data contained in each layer of each tile. It was intended to give the user an immediate idea of the contents of an area. The master thematic index provided summary thematic information for all the tiles in the database; it was provided to facilitate cross-disc queries or to build adaptive menus for selected areas not on the current disc. (Because the number of discs needed for the DCW database was four instead of the twenty-five originally thought necessary, this index was later deleted as unnecessary.)

Testing. Since there was no actual CD–ROM to test, all tests were carried out by using a CD–ROM publishing system, a series of programs designed to simulate different players on the CD–ROM production premastering hardware.

Analysis and Refinement. The analysis of the test results revealed the following:

- File access was faster for directories of less than forty names.
- Increasing the RAM buffer gave faster access only on very large directories (those with more than thirty names).
- File access was faster for files at the beginning of a CD–ROM disc.
- Sequential access to adjoining files was faster than nonsequential access.
- The performance of different CD–ROM drive models manufactured by different vendors differed significantly. Three drives were selected for further study as representative of a range of drives of reasonable performance.

Prototype 3 Results

Optimization. The system optimizations based upon the findings from Prototype 2 were to keep all directories less than thirty names; to arrange files in sequential order (the order in which they were read); and to test all candidate tiling schemes.

Testing. Testing was done on the minimum configuration machine (80286 model machine with peripherals). The CD–ROM drive was tested. To obtain additional information about the software–platform interaction, a more powerful 80386 platform was also tested.

Analysis and Refinement. The overall drawing times for Prototype 3 were two to three times as fast for Prototype 2. The time savings was due partly to the optimization described above and partly to software additions and improvements in areas that could not be tested in Prototype 2.

The difference in performance (draw times) for data accessed from the CD–ROM and data accessed from the hard disk were more pronounced on the faster platforms. This result revealed that the platform was the limiting factor on performance and not the CD–ROM media.

A tiling test was conducted to determine the tile size that optimized performance and storage efficiency while incurring the least storage and performance overhead. The tests revealed that 1-by-1-degree tiles generally involved a performance penalty and definitely carried a high storage overhead. At the larger end of the tile size scale, 8-by-14-degree tiles also carried a performance penalty, since large-file search times were so poor.

Three hardware models were tested to identify the platform and media characteristics that affected performance. The tests showed that platform speed was affected by raw clock speed, data bus width, internal cache memory, and the integration of the platform's components (CPU, bus, cache, RAM, and media). Media speed was affected by average access time, nominal bulk data transfer rate, fragmentation, latency, and interleaving.

Prototype 4 Results

Optimization. Optimizations implemented and tested in Prototype 4 included the following:

- Long seeks were removed, the largest files were reduced to less than 1 megabyte (MB), and concurrent hard disk scans were implemented, where possible, for large files that had to be read together.
- Files were arranged in the order read, with index files immediately before their data.
- Each file was opened and read only once. Files read many times were put into RAM or hard disk.
- Index files were put into RAM.
- Directories were located immediately before their files.
- Directories were kept at less than forty names.
- Primitive files were read sequentially, in a single, forward pass (except for polygons).
- Low level input/output code was sped up to reduce latency.

Testing. The testing of Prototype 4 included the following procedures: source code analysis, the running of specially marked versions of software, the examination of raw program run data, the running of database management programs, the generation of output tables, the generation of analysis tables, stopwatch verification, the generation of production quality control reports, and the generation of text reports.

The source code was analyzed to identify software input and output routines, database-specific routines, and any potential trouble areas for performance. Specific codes were added to these areas to report the time taken and the number of loops called.

Specially marked versions of software were run to isolate and detect the most time-consuming parts of the software. The end result was the production of precise timing figures down to the finest subdivisions of the program (the precision of the timing figures was limited only by the timer resolution of the hardware itself).

Raw program run data were output data contained in an output file that listed the program marks identifying each part of the program in sequence. These raw data were useful for checking a run step by step to see which commands occurred in which order and how long each command took.

Database management programs were written and used to provide automated database handling of the output data files. These programs were run on an 80386 computer; output was accepted over a serial link from the test platform. This procedure allowed tests to be run uninterrupted while their results were being processed.

Output tables were generated; they contained three parts. The first part was a summary of total data count and total time for each activity. The second part was a frequency analysis of each activity, which was used as a statistical tool to monitor and control timer resolution problems. The third was a list of the sequential file positions of the files used to monitor the number of nonsequential seeks in each file.

Analysis tables were output tables collated by overall function in order to collect total times for each VPF file structure or DCW function.

Stopwatch verification was used to provide real-time verification of the program times produced at each step in the process. They were especially useful for evaluating the analysis tables.

Production quality control reports were used as an independent verification of the database content in each of the test data selections.

Text reports were used to determine the database content of each test data selection, in order to tie the times observed to real data features, and to ensure that the different ways the tests run continued to utilize identical sets of data.

Analysis and Refinement. The performance of Prototype 4 was compared to that of Prototype 3. Edge drawing was faster, especially for elevation data. However, face drawing was many times slower and alone accounted for an overall decrease in performance. Prototype 3 used a CD–ROM-optimized, redundant data index to shade polygons. This structure violated VPF rules, and it was replaced in Prototype 4 by a nonoptimized four-file polygon structure.

An 80486 class machine was included in the Prototype 4 testing. The use of an 80386 or 80486 instead of an 80286 class machine with the same CD–ROM drive and controller markedly increased CD–ROM performance. However, the performance of the 80486 was no better than that of the 80386, even though the 80486 hard disk was almost twice as fast. This

was consistent with a CPU limitation rather than a media limitation. The hard disk times all appeared much faster than the CD–ROM, which might tend to imply that the CD–ROM media was a limiting factor after all. In the Prototype 4 analysis, it was also found that the media could be constrained by the method of file access.

As in the Prototype 3 testing, a software model breakdown was used to evaluate the functioning of the DCW application software. The software model times revealed that the tile structure was being used inefficiently. An immediate optimization was attempted in which a few small changes were made to the software; the improvement in the tile-dependent times was immediately apparent, illustrating the power of software modeling and test methodology tools developed during Prototype 4.

The question of the optimum tiling scheme for performance was revised in Prototype 4. Two final candidate tiling schemes, 3 by 3 degrees and 5 by 5 degrees, were selected and tested in this prototype. Performance times for the 5-by-5-degree tiling scheme were reasonable. By comparison with the 3-by-3-degree tiles, there was no performance degradation when drawing small or large windows, and storage efficiency was better.

2.3.4.4 Summary

The original objective of the indexing studies was to evaluate the indexing of the CD–ROMs only and, in effect, to provide optimum capability and data access speeds. During the studies, it was found that the original approach failed to address adequately the overriding concern of performance. Performance problems were found to be caused mainly by the interaction of the hardware and software components of the DCW. Optimization could not be achieved by focusing on one performance component, like CD–ROM indexing or software functionality. The solution was to adopt an integrated approach in which all project goals and all hardware and software components were considered.

A methodology was developed and applied to Prototypes 2 through 4 to address and resolve the indexing and performance problems. The methodology included the four-step cycle of optimization, testing, analysis, and refinement. The results of each prototype were examined and used to refine the indexing and performance of the next.

2.3.5 Geographic Organization Study

The geographic organization study was undertaken to define the optimal distribution of data for storage on the CD–ROM media. The research was performed in two phases described respectively in the Initial Geographic Organization Study and the Final Geographic Organization Study. The initial study discussed geographic organization in terms of a number of factors, including traditional geographic regional groupings. The final version of the study integrated data volume and scheduling issues in the discussion. The study results and recommendations were made in the final study.

2.3.5.1 Objective

The DCW database contains about 1,700 MB of data, which is well in excess of the capacity of a single CD–ROM. Therefore, the DCW database had to be partitioned into distinct subsets on individual CD–ROMs, while still retaining the characteristics of a single database. The

objective of the geographic organization study was to define the final physical organization of the DCW database on the CD–ROM storage media.

2.3.5.2 Constraining Factors

A number of factors were considered in determining the optimum distribution of data among CD–ROMs, including traditional cartographic or cultural themes, the manner in which a user would interact with the database (applications), data volumes, and project scheduling.

Logical Groupings of the Geographic Areas

The study indicated that the DCW geographic organization should be based in part on traditional views of geography. Prevalent themes in global geographic groupings include country borders, physiographic regions, and cultural (language or religious) groups. It was also desirable for the DCW geographic organization to reflect contemporary factors, such as economic relationships and geopolitics.

Data Volume

Data volume was one of the important factors to be considered in the division of DCW geographic organization. Each CD–ROM allows for the practical storage of 500 MB of data. Any proposed geographic organization had to work within this physical media constraint.

Applications Software

The DCW package includes the VPFVIEW software package that allows the user to view the database on a personal computer. The software allows the user to load and unload discs as the area of interest moves across the data boundaries between discs. The study acknowledged the usefulness of this capability but found working on a single disc to be most desirable because of the flexibility it affords the user engaged in map composition and data review. For this reason, "overlap areas" were created between discs (some data were duplicated on more than one disc) to allow continuity of anticipated areas of interest. The desirability of creating overlap areas was further supported by the fact that the DCW, as a 1:1,000,000-scale product, is perhaps best suited for regional applications, rather than global or continental ones; the density and volume of DCW data far exceed those that can be analyzed or displayed at global or continental scales.

Another characteristic of the DCW database is that it can be used outside the DCW application software environment, on user GIS and digital mapping systems. If they are used in this way, the DCW CD–ROMs essentially act as a data storage/transfer media, and it therefore becomes desirable for the data to be contained on as few discs as possible, and for the discs to be packed in space-efficient containers.

Scheduling

Because of the demanding production schedule, the premastering and mastering of the first CD–ROM were started while other portions of the database were still in the early stages of production. As a result, the geographic organization was affected to some extent by the production schedule. However, an effort was made to minimize these effects on the DCW's final geographic organization.

2.3.5.3 Final Organization

The Final Geographic Organization Study recommended that four CD-ROMs be used and that they contain the following four geographic areas of the globe: (1) North America, (2) Europe/Northern Asia, (3) South America/Africa/Antarctica, and (4) Southern Asia/Australia. This geographic organization was based first on logical geographic groupings; common physiographic and cultural regions were preserved whenever possible. The area of overlap on each disc was based primarily on cultural and geopolitical associations. Nondata tiles (tiles containing open ocean) were carefully assigned to encompass major regional ocean basins and other features. This last criterion was developed to support possible future bathymetric data enhancements of the database.

Each disc contains approximately 430 MB of data, thereby roughly equalizing the distribution of data volume on the discs. The data distribution allows for significant additional data to be added to future editions of the DCW product without altering the DCW geographic organization.

2.3.6 Symbolization Study

The symbolization study was undertaken to determine how best to display the DCW with VPFVIEW. Tasks included identifying symbolization requirements and constraints and designing and implementing appropriate symbol sets and tables. The study also identified some ways users could optimize display quality.

2.3.6.1 Symbolization Requirements

Because the DCW was created from ONCs, one goal of the symbolization design was to maintain the graphic portrayal of ONC symbology where feasible, even though ONC symbology was not designed for digital display. According to their comments on the prototypes, users expected the DCW to retain the ONC symbology. However, the traditional design elements needed to be compatible with the capabilities of an interactive electronic display. For example, the symbology had to be fully compatible with the changing scales that would result when users employed the "zoom in" and "zoom out" commands.

2.3.6.2 Symbolization Constraints

The major constraints on the design of the display symbology were the resolution of the minimum configuration monitor, the capabilities of the C graphics libraries, and the capabilities of VPFVIEW (see Section 2.5.3 for a description of the VPFVIEW hardware and software environment). Of these factors, the resolution of the monitor (12-inch medium resolution color monitor [EGA 640 x 30 resolution]) was the primary constraint, because it affected the appearance of the point symbols, linework, area patterns, and typography.

The C programming language was used in the development of VPFVIEW. The basic graphic symbology of the C graphics libraries was another major constraint on the development of the DCW symbology, especially in regard to line weights and area fill patterns.

2.3.6.3 Symbolization Implementation

The symbology implemented in the DCW was developed throughout the prototyping process. Initial symbology was introduced with Prototype 3, and it continued to evolve through and past Prototype 4. Comments and suggestions on Prototypes 3 and 4 were incorporated in the final DCW symbol sets.

A default symbology was implemented to provide the user with an immediate and adequate symbology for all the data in the DCW. ONC symbols were retained where they logically could be. However, given the default symbology constraints, VPFVIEW was enhanced to allow users to define changes in the symbology. Within VPFVIEW, the user can change the symbols used for point and line features and has access to a sixteen-color palette and three text fonts. These functions allow users to support a specific application or data orientation by resymbolizing and regrouping features for clarity.

2.3.6.4 Optimizing Graphic Displays

In addition to discussing the factors that led to the symbolization finally implemented, the symbolization study outlined ways users could optimize display quality. Specifically, it recommended that users do the following:

- Display as few features as possible.
- Since color is the only usable means of distinguishing features at scales smaller than 1:1,000,000, reserve color for significant differentiations.
- Since background area tints make text, point, and line symbols difficult to read, fill polygons only when necessary.
- Relate color groupings (by hue) and progressions (by value or brightness) to feature groupings (avoid assigning them randomly).

2.3.7 DCW Error Analysis

An error analysis for the spatial data in the DCW database was performed as one of the special studies for the DCW. The study was stated in the early phases of production and completed in February 1991. The following summarizes the objectives of error analysis, the methodology used to perform the study, and the study results and recommendations.

2.3.7.1 Objectives

The main objective of the DCW error analysis was to compile a list of all error sources influencing DCW database accuracy and to perform an error propagation analysis. This study was limited to the positional accuracy of the automated database from the ONC series. Other accuracies, including those pertaining to attribute accuracy, data completeness and logical consistency, and quality of lineage, were not included in the study.

2.3.7.2 Requirements for the DCW Error Analysis

Typically, error propagation analyses for spatial data require an analysis of all positional errors introduced during the compilation and automation of the spatial data. Positional error is defined as the deviation of features from their true location in each coordinate direction, where the true location of those features is usually derived from existing sources of higher accuracy or from a field surveying check of higher accuracy.

Horizontal accuracy is usually stated as a circular error, and vertical accuracy as a linear error, at a specified confidence level. Linear errors are used to express the vertical error in the Z-coordinate direction. Both circular and linear errors are derived from standard deviations in each coordinate direction. In accordance with these conventions, the horizontal position accuracy in the DCW error analysis was represented in terms of circular error, and the vertical accuracy was represented in terms of a linear error, both at a 90 percent confidence interval.

As indicated in the error analysis study, errors were introduced during each of the mapping and automation processes. Since the DCW database was developed based on the ONC series and the exact ONC chart histories were unknown, no estimate could be given for errors introduced at each ONC production process. However, the degree of error introduced into the DCW during automation was estimated by measuring the displacement of points from their true position at certain steps during the DCW production process. Since the accuracy of an original ONC sheet was known, an overall accuracy for the same DCW module could be obtained by computing the root sum square of the ONC error and the DCW automation error.

It was presumed that if the errors for the DCW production process had been estimated reliably, the DCW accuracy derived by computing the root sum square of the ONC error and the DCW automation error would be similar in magnitude to the error derived by comparing DCW data to a source of higher accuracy. Therefore, the following requirements were established for the error analysis study:

- Overall DCW accuracy was to be estimated through an independent test by comparing DCW data to a source of higher accuracy. The first fully automated ONC map sheet, ONC G-18, was chosen for this part of the analysis.

- Errors introduced into the data by basic processing/automation and advanced DCW processing were to be estimated. The basic processing of DCW data included manuscript preparation and drafting, scanning and digitizing, and editing. Advanced processing included the projection of data into real-world coordinates, edge matching, and tiling. Positional errors introduced by DCW processing were to be estimated by subjecting test data containing features of known position to the standard DCW production process and measuring the displacement of test points at selected steps during the production process.

- With the known accuracy of ONC G-18 and the production error estimate, a DCW error estimate was to be computed through a root sum square computation.

- Such aspects of data quality as completeness, attribute accuracy, and data consistency were not addressed in this report.

2.3.7.3 Methodology of Determining Positional Accuracy

Independent Test Using Sources of Higher Accuracy

According to the Merchant 1987 study cited in the error analysis report, the horizontal and vertical accuracy of spatial data can be determined by comparing the position of a representative sample of well-defined points in the spatial data to the position of the same points in a source of higher accuracy. Sample means and sample standard deviations were then computed independently for all three coordinate directions. Once these quantities were known, conventional hypothesis testing was employed to determine whether the spatial data contained systematic error or whether the data met a previously established accuracy standard.

USGS 1:24,000-scale maps were selected as the source of higher accuracy. For a source of 1:24,000-scale map, National Map Accuracy Standards specify a circular error of 0.51 millimeter at map scale at a 90 percent confidence level. This translates to an error of 40.1 feet at ground scale. Spatial data of 1:1,000,000 typically have horizontal errors of between 1,640 feet and 8,200 feet associated with them, depending on the primary use of the spatial data. Compared with an error of this magnitude, an error of 40 feet in a 1:24,000 USGS sheet is virtually negligible. For purposes of positional accuracy testing, the USGS map sheets were therefore considered error free.

Accuracy computations were based on a total of thirty-nine well-defined test points. Test points were selected from two scanned and two manually digitized layers (roads, drainage, railroads, utility lines) and consisted of "between layer" as well as "within layer" intersections. This methodology was used to ensure that the DCW G-18 accuracy statement could be considered representative for all database layers.

Estimation of Production Errors

In order to estimate production errors, a test graphic of dimensions 7.5 inches by 7.5 inches was developed. The test graphic contained arbitrary linear features and simple geometric features. It was produced as a single-precision ARC/INFO coverage by entering all feature coordinates manually through the keyboard. Therefore, the position of all features in the test data was accurately known.

The test graphic was initially subjected to the basic processing steps of manuscript preparation/drafting, scanning/digitizing, and editing. A sample of thirty points was then extracted, and their coordinates were compared to the coordinates in the original test graphic. Basic production errors were reported as a circular error using a 90 percent confidence interval. The data were then subjected to the advanced processing steps of projection, edge matching, and tiling. Sample points were again extracted, and their coordinates compared to the coordinates in the original test graphic, in order to determine the degree of error introduced during advanced processing.

2.3.7.4 Results and Discussion

The Circular Map Accuracy Standard (CMAS) calculated from the standard deviations in the X- and Y-coordinate directions was found to be 3,670 feet, meaning that 90 percent of all well-defined points can be expected to be within 3,670 feet of their true position. This compared with an error of 2,500 feet in the original ONC and, through a root sum square subtraction, led

to an initial production error estimate of 1,104 feet. The linear map accuracy standard for vertical accuracy of the automated DCW sheet was found to be 453 feet. The comparable accuracy given for the ONC G-18 was 500 feet. Since the vertical error in the DCW G-18 did not exceed 500 feet, it was concluded in the study report that during DCW production no vertical error was introduced into the data.

DCW automation errors due to basic processing, when translated to ground scale for a product of scale 1:1,000,000, was found to be 1,099 feet for scanned data, 1,277 feet for digitized data, and 1,309 feet for data that were first manually drafted off the test data and then scanned. During advanced processing steps, very little additional noticeable positional error was introduced into the test data. It was therefore concluded that almost all positional error inherent in the DCW production process was introduced during basic processing.

This was not unexpected, since advanced processing relied mainly on automated routines. Errors during advanced processing would therefore be mainly due to software limitations and possible loss in coordinate precision.

Both the ARC/INFO software and the DCW production process were designed to minimize errors from these sources. The results of advanced processing of test data indicated that these objectives had indeed been achieved. The results of all tests showed that errors introduced into the DCW during its automation were of acceptable magnitude. In particular, production error estimates for each automation type were found to be similar in magnitude to the error estimated from the independent test of higher accuracy.

2.3.7.5 Conclusions and Recommendations

The following conclusions were reached as a result of the study:

- The horizontal accuracy of the DCW automated from ONC G-18 was 3,670 feet at a confidence level of 90 percent. This was compared to an accuracy of 3,500 feet (including printing error) of the original ONC G-18.

- The vertical accuracy of the DCW automated from ONC G-18 was 453 feet at a confidence level of 90 percent. This was somewhat less than the 500 feet stated as the vertical accuracy for ONC G-18. It was therefore concluded that no further vertical error was introduced into the elevation data during DCW production.

- Based on the overall accuracy obtained for the DCW G-18 and the accuracy published for ONC G-18, DCW production error was initially estimated at 1,180 feet.

The magnitude of the error introduced into DCW data during the DCW production process was estimated from test data, and was measured separately for digitized, hand drafted/scanned, and scanned-only coverages. Results indicated the following:

- The errors introduced during the DCW database automation were of acceptable magnitude.

- At ground scale, production errors were found to be 1,099 feet for scanned coverages, 1,277 feet for the digitized coverages, and 1,309 feet for hand drafted/scanned coverages for a product at scale 1:1,000,000.

- The magnitude of production errors estimated by using test data was in close correspondence with that initially estimated (1,180 feet) after an independent determination of the accuracy of DCW G-18. It was therefore concluded that the errors estimated for the DCW production process were essentially reliable.

The results of the error analysis study have led to the adoption of the following recommendations in the DCW database production:

- Since the errors estimated for the production process seemed to be reliable, the accuracy of individual ONC sheets, in conjunction with the accuracy of the DCW production process, should be used to derive the accuracy of each DCW production module through a root sum square calculation.

- During DCW production, it was important to maintain consistency in the magnitude of errors introduced into DCW data automation. A procedure was therefore implemented to test the accuracy of the DCW production process at selected intervals.

2.4 Vector Product Format Military Standard Development

The major goal of the DCW prototyping phase was to create a generic standard that serves as a basis for multiple digital vector mapping, charting, and geodesy products. The vector product format (VPF) standard was developed to this end. In fact, although the DCW database stands as a monumental achievement of the DCW project, its primary initial use was to test and verify VPF concepts.

As discussed in Section 2.2, VPF was developed during the DCW prototyping stage. Work on concepts leading toward VPF began in the spring of 1990. A complete VPF standard was created by ESRI in the spring of 1991, and it was incorporated into Edition 1.0 of the Digital Geographic Information Exchange Standard (or DIGEST) in June of 1991. DIGEST is now composed of two standards, its original "exchange" version and also VPF. (Within DIGEST, VPF is known as the Vector Relational Format, or VRF; VPF and VRF are identical.)

After June 1991, additional requests-for-change (RFCs) were approved, resulting in both editorial modifications and additional VPF optional functions. In late 1991, VPF was reviewed by both DMA and over fifty DOD organizations and offices. This review was the source of most of the RFCs of 1991 and early 1992. In April 1992, after all DOD comments had been addressed, the *Vector Product Format Military Standard* (MIL-STD-600006) was released by DMA to the Defense Printing Service for distribution to all DOD agencies and the public. This release of VPF is known as VPF Version 1.0.

The key aspect of the utility of VPF is that VPF is the first "direct-use" standard. Section 2.4.2 defines and discusses the direct-use concept. Initially, however, in Section 2.4.1, existing exchange standards are discussed to allow comparison of the concepts of "exchange" and "direct use." Section 2.4.3 describes the design goals of VPF development, and Section 2.4.4 describes all the georelational characteristics and components of VPF. Section 2.4.5 briefly lists other VPF characteristics, and Section 2.4.6 is a summary. A complete description of VPF is found in the VPF standard (MIL-STD-600006), which is available from the address listed in Appendix B.

2.4.1 Existing Exchange Standards

During 1991, the Spatial Data Transfer Standard (SDTS) was placed in the Federal Register by USGS for final public comment before its adoption as a Federal Information Processing Standard (FIPS). Work on this standard began in 1982, by a series of committees composed of government, university, and industry representatives. Its fundamental mission is to develop a standard for the transfer of spatial data—particularly for the transfer of data on magnetic tape.

In 1988, the military mapping organizations in nine countries (Belgium, Canada, France, Germany, Italy, Netherlands, Spain, United Kingdom, and the United States) formed a standards committee called the Digital Geographic Information Working Group (or DGIWG), which has produced another transfer standard known as DIGEST. The sponsoring organization in Canada is the Directorate of Geographic Operations of the Canadian Directorate of National Defense. The sponsoring organization in the United States is the Plans and Requirements Directorate of the Defense Mapping Agency (DMA). DIGEST uses a particular, hierarchical feature/attribute coding standard known as the Feature Attribute Coding Catalog (FACC).

According to Section 1.0 of DIGEST (Edition 1.0, June 1991), the purpose of DIGEST is to "enable interoperability and compatibility among national and multinational systems and users. [DIGEST] will also support the increasing use of joint development programs. In fact, it is essential that geographic staffs included in the development of national Geographic Information Systems ensure that the data structures and feature/attribute coding schemes are compatible with these standards...[DIGEST] applies to the topographic, hydrographic and aeronautical institutions of the participating nations. [DIGEST] has been built to support exchange of digital Geo data between the central agencies operating in the geo scientific field."

Standards such as SDTS and DIGEST use the underlying model of a tape transfer—a sequential file constructed to be read once from beginning to end to load a database into the target system. Both standards use ISO 8211—a standard developed by information exchange specialists to provide a self-describing exchange. ISO 8211 has to be read in a strictly sequential order to understand the content. The approaches of these two standards are fine for their intended purpose, cartographic data exchange.

2.4.2 VPF—The First Direct-Use Standard

VPF was developed to be a *direct-use* standard, not a transfer standard. The goal of VPF is to allow users to build database products in this standard, and then use the products directly by GIS software systems. VPF is designed for media that can be used directly and interactively by software—magnetic hard disks and optical compact discs with read-only memory (CD-ROMs). VPF must provide for random access to each individual record without scanning a whole CD-ROM or hard disk; hence, it must provide most of the services of an internal database manager of an integrated GIS software package, including supplying descriptive schema definition tables.

Like SDTS and DIGEST, VPF is "self-describing," meaning that it has schema definition tables built into the data content; but unlike SDTS and DIGEST, these schema definition tables can be accessed whenever needed by software, instead of in a strictly sequential order. Therefore, using these schema tables, software can determine the database design of the actual

data. The schema tables (also known as metadata—or data about data) can also be directly displayed to the user to support on-line data dictionary functions, legend functions, data quality descriptions, geographic reference (or "inset") maps, or the presentation of other information that is normally found on the borders of printed maps.

Another requirement for a user-oriented data standard is that it be able to represent a wide variety of databases. VPF is based on a single, general model that supports a wide variety of data, including integrated and layered products and complex and simple product schemas. In contrast, interchange formats must support multiple data models, providing for the interchange between them. Thus, interchange formats are not directly readable by any single application. Since VPF relies upon a single data model, it permits the development of generic software and allows the direct use of geodata.

2.4.3 VPF Design Goals

In addition to the direct use design goal described above, three other goals are accomplished by VPF:

- VPF supports GIS applications
- VPF is compatible with DIGEST
- VPF will directly support data quality information

These goals are reviewed in detail below.

2.4.3.1 VPF Support of GIS Applications

A geographic data model consists of three parts: objects, operators, and rules. Even though VPF is a database format describing only objects, the designers of VPF understood and accounted for issues associated with the future development of operators and rules needed for a fully functional GIS. VPF is based upon the same georelational model as many commercial GIS formats and systems, including ARC/INFO, ODYSSEY, DLG, TIGER, SYSTEM 9, and others. The georelational model provides a foundation for a GIS, allowing the definition of operators that act upon spatial location information and thematic information, across geometry, topology, and attribute tables. In addition, VPF goes beyond current commercial GIS formats to include specific definitions for formal data quality modeling, complex geographic features composed of different topological types, active and passive data dictionaries, support for both tiling and the seamless assembly of tiles, support for cross-tile topology, and support for ANSI-SPARC user view modeling.

2.4.3.2 VPF/DIGEST Compatibility

VPF was developed at a time when a significant international interchange standard for geographic data known as DIGEST was being formulated. Although the direct use objective placed a different design goal on VPF, VPF was still designed to be compatible with DIGEST. This compatibility appears in the terminology used, and accounts for most of the system-defined file suffixes.

Beginning in June 1991, VPF and DIGEST became even more closely linked. At that time, DIGEST incorporated the VPF georelational model for vector data into its family of standards. (Within DIGEST, VPF is known as vector relational format.) Thus, DIGEST contains both an exchange format and a direct-use format. VPF continued to undergo development during 1991, and a revised version of VPF was incorporated into DIGEST Version 1.1 in the fall of 1991. It is anticipated that the relationship of VPF as a component of DIGEST will continue into the future.

2.4.3.3 VPF Support of Data Quality Information

VPF allows for the storage of data quality information to permit the evaluation of the data for particular applications. Although the exact form of the data quality information supplied for a database is set by a product specification, VPF supports incorporation of data quality information at each structural level in the database (see Table 3). Data quality information may be stored at any VPF level. When it exists at a given level, it applies to all data at or below that level. However, when data quality information exists at multiple levels, the information stored at lower levels always takes precedence over that at the higher levels.

Table 3. VPF Data Quality Information

Level	Location of Data Quality Attributes	Location of Data Quality Coverages
Database	In the data quality table within the database directory.	Within the database directory.
Library	In the data quality table within the library directory.	Within the library directory.
Coverage	In the data quality table within the coverage directory.	"Layer-equivalent" data quality coverages.
Feature	In the feature attribute table.	Not applicable.
Primitive	In the primitive table.	Not applicable.

A VPF database may contain seven types of data quality information: source, positional accuracy, attribute accuracy, date status, logical consistency, feature completeness, and attribute completeness. The extent of the data quality information contained in a product and the types of data quality to be included are determined by the product specification.

As shown by Table 3, data quality information can be represented as an attribute or as a coverage. In the case of attributes, data quality information may be added to an existing VPF table, stored in a separate table, or stored in a special data quality table.

2.4.4 The VPF Georelational Model

VPF uses a combination of the relational and planar topological data models to provide a powerful hybrid for a spatial database within a GIS. The VPF georelational model provides the data structures for a spatial database, whereas a GIS provides the rules and operators that manipulate topology, geometry, and relational objects in the form of tables. Whenever an operation requires thematic information, the use of relational and topologic table operations are used to supply the result. If the operation is spatially related, the use of geometry and topology together will be used. This triad of principles (geometry, topology, and relational tables) provides a robust database architecture for VPF. A geometric model would only use geometry and relational tables together. (Note: Additional background regarding the three models used by VPF is provided in Appendix A of the VPF military standard.)

2.4.4.1 VPF Thematic Objects

VPF thematic data objects consist of information that is a combination of structural data organization (directories) and information stored in tables, such as metadata and feature attributes.

VPF organizes its geographic objects by means of database, library, and coverage directories. The database directory consists of a set of libraries, in addition to any tables that supply information to the entire database. A library directory references the extent of the geographic information contained within it. All other VPF structures are confined to libraries. A coverage directory defines the topologic and thematic relationships of features. The coverage can be thought of as a map sheet in its digital form. All the geographic feature information of a coverage is contained within it.

Within VPF tables, thematic information is stored as attributes and metadata. Attributes are used to express more information concerning the geometric and topologic primitives of the database. For instance, a river feature may carry a variety of attributes that help to define the geographic object, describing river width, depth, flow rate, and flood level. Metadata provides general information about the geographic data within a database, library, or coverage. For example, a geographic reference table is used to determine the spatial extent of a library. Schema tables are another form of metadata and are used to navigate through these directory structures, defining the relationships within them. These schema tables are required to provide the information necessary to access the database without associated software having predetermined knowledge of the data structure organization.

2.4.4.2 VPF Topologic Objects

VPF topologic objects define feature relationships. A feature is composed of geometric and thematic tables. There are three feature types in VPF: point, line, and area tables, which contain the topological constructs of, respectively, the node, edge, and face primitives. Feature tables also usually contain attribute information, but they are mainly used to define these topologic constructs.

For instance, a landmark (oil well or television tower) can be defined as a point feature, which relates to the node primitive table. The landmark's topologic information, in addition to thematic information (such as height, material, and construction), contains any relations to a surrounding area feature or connecting line features.

An example of a linear feature is a road. Each road feature maintains a geometric relation with an edge primitive. The road will have a start node and an end node, which define a geometric direction. Each road feature is part of a network; that is, information is contained within the database as to which roads intersect any other given road at each node. Any given road will always maintain a left- and right-neighbor relationship with an area feature, if one exists.

A lake is an example of an area feature. In addition to being related to attributes, a lake is related to face primitives. A lake is topologically related to any other feature that is found within it (islands) or that touches its borders (rivers, springs, or streams).

2.4.4.3 VPF Geometric Objects

In VPF, features are created from four basic geometric object primitives: nodes, edges, faces, and text. Node, edge, and face primitives are used to represent, or model the geometric component of, real-world geographic phenomena. *Nodes* are zero-dimensional primitives used to represent the geometric component of singularly discrete geographic phenomena, or to link edges together. *Edges* are one-dimensional primitives used to represent the geometric components of linear geographic phenomena. *Faces* are two-dimensional primitives representing areas' enclosed edges and are used to model the geometric components of area features. The *text* primitive is a cartographic primitive rather than a geographic primitive; it does not represent anything in the real world but allows the placement of textual information to be stored in the database without being tied to any particular feature. The text primitive allows identification of regions without specific boundaries such as the Rocky Mountains or the North Pacific Ocean.

2.4.5 Additional VPF Characteristics

VPF is a neutral, machine-independent format design that must be combined with a product specification to develop a given product. VPF does not contain product-specific information such as particular feature coding schemes or special relationships between features. VPF allows such information to be encoded and described, but this information is not part of VPF itself. Neither does VPF define the geographic entities and objects to be represented. Instead, these product-specific design details are carried in the product specification.

VPF provides logically continuous topological relationships, even when the database is physically partitioned into tiles. VPF is able to manage data that cross the tile boundaries through a mechanism called "winged-edge" topology, which implants information about features on the left (or right or top or bottom) of a tile boundary into each feature that touches the right (or left or bottom or top) side of the boundary.

The VPF is designed to support varying levels of topology and varying degrees of integration. The georelational approach allows data to be separated into layers. When applications do not require querying the relationship among data types, data can be stored and accessed efficiently in separate layers. When such queries are required, the layers—carrying full topological relationships—can be integrated.

For a complete description of VPF, refer to the VPF military standard, which is available through the address provided in Appendix B.

2.4.6 Summary

VPF is a standard format, structure, and organization for large geographic databases. VPF is based on a georelational data model and supports direct-use applications. VPF is designed to be compatible with a wide variety of applications and products. VPF allows application software to read data directly from computer-readable media without prior conversion to an intermediate form. VPF uses tables and indexes that permit direct access by spatial location and thematic content and is designed to be used with any digital geographic data in vector format that can be represented using nodes, edges, and faces. VPF defines the format of data objects, and the georelational data model provides a data organization within which software can manipulate the VPF data objects. A product specification corresponding to a specific database product determines the precise contents of feature tables and their relationships in the database. In this context, each separate product or application is defined by a product specification and implemented by using VPF structures.

2.5 VPFVIEW Software Development

2.5.1 Introduction

In the past, the Defense Mapping Agency (DMA) has produced a variety of digital prototype and production products. Most of these products did not provide the prospective user with an effective way to review the data set prior to delivery; the data sets were usually distributed either with no software or with very limited software. The user had to base an evaluation of the usefulness of the data set on the documentation provided or expend the effort necessary to write access routines. With the creation of large database products like the DCW, the need for effective review tools became apparent. What was needed was a software system that would present the data set and demonstrate some of its basic uses. Data set users provided with a system of this type would have both clear, operating examples of data access and a model for the development of user software applications.

Because DMA recognized the value of demonstration software, one of the objectives of the DCW project was to develop an effective tool for the demonstration and review of the DCW data set. Another was to provide a toolbox of program tools with the DCW that would allow the user to develop additional applications based upon the DCW product. These objectives were met with the development of the VPFVIEW software product that was distributed with the DCW database.

Starting from Prototype 4, significant progress was made in developing a generic application software product called VPFVIEW to allow display of all data structured in accordance with VPF. The refinement of VPFVIEW continued until recently.

2.5.2 Overview of VPFVIEW Chronological Development

The DCW application software (which was later named VPFVIEW) was designed through prototyping. The design approach was to build a functional, useful prototype, and then modify the prototype through user feedback. Software prototypes, delivery dates, and the design focus of each prototype development effort are listed in Table 4.

Table 4. VPFVIEW Software Prototypes

Prototype	Delivery Date	Design Emphasis
DCW Application Software Prototype 2 (DOS)	April 1990	Conceptual design of the user interface
DCW Application Software Prototype 3 (DOS)	Aug. 1990	Complete user interface and preliminary program functions
DCW Application Software Prototype 4 (DOS)	Dec. 1990	Complete software for use with (only) DCW
VPFVIEW Prototype 1 (DOS)	May 1991	Conceptual design of View and Theme functions to allow use with all VPF products
VPFVIEW Prototype 2 (DOS)	Oct. 1991	Preliminary design of all generic-VPFVIEW functions and incorporation of unit and integration testing error fixes
VPFVIEW Product (DOS)	March 1992	Incorporation of functional testing error fixes. Distribution version for the DCW database
VPFVIEW–UNIX port version	June 1992	Porting of the DOS version to UNIX
VPFVIEW–UNIX alpha version	Aug. 1992	Incorporation of join-table and complex feature handling based on the TESTDTLM database
VPFVIEW–UNIX beta version (planned)	Oct. 1992	Incorporation of multilibrary and multidatabase display capabilities
VPFVIEW–UNIX final version (planned)	Dec. 1992	Incorporation of unit, integration, and functional testing error fixes

Table 4 shows that from 1990 to 1992 there were three distinct development phases for the VPFVIEW software. Initially, in accordance with the original DCW contract, the DCW applications software was designed and developed purely for use with the DCW database. This development phase continued throughout 1990, as shown in Table 4.

However, early in 1991, DMA recognized the value of expanding the DCW applications software into a generic software product that would accomplish functions similar to those of the original software (namely, database demonstration), but would also be able to display any database developed in accordance with the VPF standard. Thus, the software development effort set out on a new tack with new functional requirements. The result of this redirection was ultimately the VPFVIEW product, which was distributed with the first edition of the DCW database in the summer of 1992. The VPFVIEW–DOS development and testing thus represents the second phase of software development in the DCW project. (Please refer again to Table 4.)

Finally, having proven that a VPF-generic software product could be implemented on a small DOS hardware platform through the release of VPFVIEW–DOS, DMA again expanded the original scope and functional requirements of the software to accomplish other user requirements unrelated to the DOS platform. These requirements will be met in the VPFVIEW–UNIX product, which is still under development. They include expanding VPFVIEW–DOS to simultaneously display multiple VPF libraries contained within one or

more VPF databases. The VPFVIEW–UNIX development and testing is occurring during the latter three-quarters of 1992, as shown in Table 4.

Most of the remainder of Section 2.5 will discuss each of these three phases in turn. Sections 2.5.4 and 2.5.5 discuss the DCW applications software design and development; Sections 2.5.6 and 2.5.7 describe VPFVIEW–DOS design, development, and testing; and Section 2.5.8 relates the VPFVIEW–UNIX design objectives, and refers to the development and upcoming testing efforts. First, however, Section 2.5.3 will list the hardware/software environments upon which the two software products were implemented and will operate.

2.5.3 VPFVIEW Hardware and Software Environments

2.5.3.1 VPFVIEW–DOS (and DCW Applications Software) Hardware and Software Environment

The recommended hardware environment for VPFVIEW–DOS is:

- Computer with an 80386 processor and an 80387 math coprocessor
- Video Graphics Array (VGA) and compatible monitor
- Mouse driver
- High-density floppy drive (5-1/4 inch or 3-1/2 inch)
- 30 MB hard drive with at least 20 percent free disk space
- 2 to 4 MB Random Access Memory (RAM)
- MS–DOS Version 3.1 or higher (except Version 4.0, which is not recommended because of its additional memory requirements)
- CD–ROM drive (ISO 9660 compatible) (optional)
- Microsoft MS–DOS CD–ROM Extensions Version 2.0 or higher (optional)
- Printer capable of reading PostScript formatted files (optional)
- Line printer (optional)

VPFVIEW–DOS will also function in the following environment:

- Computer with an 80286 processor and an 80287 math coprocessor
- 1 MB RAM
- Enhanced Graphics Adapter (EGA) and compatible monitor
- Arrow key interface

2.5.3.2 VPFVIEW–UNIX Hardware and Software Environment

Although VPFVIEW–UNIX will operate on systems with less capability, the recommended hardware and software environment for VPFVIEW–UNIX is:

- Sun SPARCstation 2
- 32 MB of internal memory
- 8-bit Sun Graphics Accelerator (GX) board
- 600 MB hard disk
- CD–ROM Small Computer Standard Interface (SCSI) device
- PostScript output device
- SunOS 4.1 or higher
- OPEN LOOK Version 3.0 windowing environment
- Sun XView libraries
- Sun X Window System

2.5.4 DCW Applications Software Design Objectives

The primary DCW applications software design objectives were to make the software both user and programmer friendly, because the software would be released in the public domain. Software design was constrained in speed and memory because of the CD–ROM and the DOS hardware/software environment. The software design requirements were that it should be used to access the DCW database implemented with VPF, display the selected features, and create reports. Therefore, the software focuses mainly on displaying the database, and its analytical capability is very limited. The software enables the user to select data for display by geographic region as well as by type, and it also enables the user to display and evaluate the database directly from CD–ROM, hard drive, or diskette without loading or converting the data. Once a display has been generated, the user can save either the data request itself or the results of the request on the hard drive. If the appropriate hardware has been connected, displays and text reports can be printed.

2.5.5 DCW Applications Software Development

As described in Section 2.2, the DCW applications software was continually modified during the four DCW prototypes in 1990. The design-by-prototyping approach meant that functions were gradually implemented and refined throughout the prototype period based on the design and comments obtained from the DCW participants.

Starting from Prototype 3, VPF data structure was implemented and new user-oriented functions were added to the software. A Browse map was added to Prototype 4 that allowed the user to zoom and pan to determine an area of interest. Another major addition to Prototype 4 was the Spatial Query function, which allowed the user to point at a location on the screen and see all the attribute information for features that fell at that location. The Prototype 4 version of the software in December 1990 was the last release of the DCW applications software. After that point, development focused on VPFVIEW–DOS, as described in Section 2.5.2. The remainder of this section (2.5.5) will describe functions that were developed within the DCW applications software, and also carried forward into the VPFVIEW–DOS and VPFVIEW–UNIX developments.

The DCW applications software was designed to utilize user-oriented menus which allow the user to easily understand and operate the software. The menu functions are activated by selection with a mouse. The cursor is placed on the desired function, a mouse button is pressed, and the function is initiated. There are as many as four levels of menus; there is a main menu, and submenus can be accessed from each of them. The main menu is composed of the System function, VPF Content function, Feature Selection function, Graphics function, Text Report function, and Archive function. The menus are arranged from left to right in the approximate sequence in which they would be used in a typical session. The main menu provided the framework upon which lower-level functions and enhancements were later added and implemented.

Options on the System menu allow the user to perform DOS operations on the files and directories on PC without leaving the application software or the DCW database. This menu was implemented to provide access to other files on the PC while the user is engaged in applications sessions with the DCW database. The VPF Contents menu options enable the user to examine the contents of the DCW database and manipulate the organization of the information within the database.

The Feature Selection menu, which comprises both a main menu and a set of submenus, enables the user to select the coverages and the associated themes that the user wants to include in the screen display or other reporting options. The Graphics menu enables the user to enhance the visual characteristics of the screen display and create files for hard copy output. The Text Report menu enables the user to generate simple text reports which provide information on features associated with coverages and themes the user selects. The user can display an area content summary to a feature location list on the screen, send it to a printer, or save it to disk.

Through the options on the Archive menu, the user can save and restore feature selection sets, symbology, screen displays, and the data specific to the user's current study area. Three lower levels of submenus under the main menu were designed to provide the user with further options and more choices in system operation, data contents accessing, feature selection, viewing, and reporting.

The detailed descriptions for menu operations can be found in the *VPFVIEW Users Manual for the Digital Chart of the World,* which is distributed with the DCW database product.

2.5.6 VPFVIEW–DOS Design

As described in Section 2.5.2, early in 1991 DMA directed ESRI to expand the functions of the DCW applications software to allow automatic and direct demonstration of any database that was formatted in accordance with the VPF military standard. It was possible to do this because data formatted in accordance with VPF include database schema tables that the software would read which define the format for the remaining data in a particular VPF database. At that point, the software was renamed as "VPFVIEW" to reflect both its VPF-generic nature and the fact that a new concept known as user "views" was added to the software concept and design.

"Views" are the mechanism by which VPFVIEW displays the results of thematic queries. Every view contains symbols for all coverages in a VPF library. VPF coverages are made up of feature classes (areas, lines, points, and text; see Section 2.4). Themes are the core of the view. Several themes may be created from each feature class in a coverage. For example, different themes may be created for different types of roads (multiple lane, single lane, tracks

and trails, and connectors), even though all roads are in the same feature class (lines) and also in the same coverage (roads). A view is the set of all themes that has been created for a coverage.

In VPFVIEW–DOS, a View submenu was implemented under the VPF Contents menu. It contains a series of lower level submenus, including select view, create view, delete view, copy view, rename view, create theme, delete theme, and modify theme. The create theme and modify theme submenus allow users to build symbology for their VPFVIEW displays.

2.5.7 VPFVIEW–DOS Development and Testing

VPFVIEW–DOS development occurred during the period from March 1991 to March 1992. As indicated in Section 2.5.2, three releases of VPFVIEW–DOS were delivered to DMA. The first release in May 1991 initially implemented the "View" and "Theme" functions. In October 1991, all VPFVIEW–DOS functions were implemented, and some of the errors identified through unit testing and integration testing of VPFVIEW were repaired. The final version was submitted in March 1992 and included all repairs for all errors identified in the unit, integration, and functional testing processes.

Software testing was conducted on VPFVIEW–DOS over a period from August 1991 until March 1992. Software testing verified error-free linkage and operation of all VPFVIEW–DOS units. Unit testing was performed by ESRI's software quality assurance organization, which was independent of the ESRI software development team. Integration testing was performed by Loral Defense Systems—Akron, Ohio. Functional testing was conducted by both organizations and witnessed by DMA software testing personnel.

Unit testing was conducted for all units of the VPFVIEW–DOS software. Unit testing is the line-by-line testing of a unit isolated from all other units. Dummy routines were generally used for some or all of the units that were subordinate to the unit being tested. Although no project requirement existed for the development of VPFVIEW in ANSI C, most VPFVIEW–DOS modules were successfully verified on an ANSI C compiler.

Integration testing involves testing a unit with its subordinate units and peers intact. Integration tests were performed on units from one or more modules, but did not generally include all the units from any one module. Integration testing was conducted for all units comprising the VPFVIEW–DOS software. An integration test report was provided to DMA in the spring of 1992.

Functional testing is the testing of each and every user-accessible function of the application program. Functional testing was performed on every external program function. The final functional test represented a single acceptance test of VPFVIEW–DOS. Functional testing was recorded via checklists. A functional test report was provided to DMA in the spring of 1992. These documents included the software test checklists and provided descriptions of problems encountered and solutions implemented.

Functional testing of VPFVIEW–DOS consisted of running the 1,903 tests described in the functional test plan, which was submitted and approved by DMA prior to the functional testing activity. Testing was conducted over the one-week period from March 16 to March 20, 1992, at ESRI. The testing was conducted by three two-person teams using three machines. Each of the three two-person teams was responsible for testing a different set of the software functions outlined in the functional test plan. As testing proceeded, each team annotated a copy of the

functional test plan, initialing those tests that were completed successfully. These three annotated copies of the functional test plan are on file at ESRI. When the full complement of 1,903 tests were complete, fifty software discrepancy reports were filed, so the software performed successfully in 97 percent of the tests. Of the fifty discrepancies, forty-four were very minor and were repaired within two days of being identified. The remaining six discrepancies, which were minor, were repaired within two weeks of being identified.

2.5.8 VPFVIEW–UNIX Design Objectives

After the release of VPFVIEW–DOS, DMA again expanded the original scope and functional requirements of the VPFVIEW software to accomplish other user requirements unrelated to the DOS platform. These requirements will be met in the VPFVIEW–UNIX product.

VPFVIEW–UNIX design efforts are currently continuing. The VPFVIEW–UNIX detailed design document was recently delivered to DMA, and two prototype versions of the software have also been delivered. Development and testing will continue throughout 1992. The VPFVIEW–UNIX 1.0 will be delivered in December of 1992.

VPFVIEW–UNIX will contain virtually the same basic functions as the DOS version, except that it will run on a Sun SPARC family workstation under the OPEN LOOK Graphical User Interface (GUI; see Section 2.5.3). Use of OPEN LOOK will result in a significantly different user "look and feel," since VPFVIEW–DOS used an application-specific GUI. VPFVIEW–UNIX will display any valid VPF version 1.0 (or earlier) dataset. The software assumes that the data conform to the VPF standard.

The primary extension of VPFVIEW–UNIX (over VPFVIEW–DOS) is that it will allow data from different VPF databases and different VPF libraries to be displayed simultaneously. Themes within a view will be able to reference different databases and libraries, as well as data from different feature classes. Because different VPF libraries can be stored in different coordinate systems, VPFVIEW–UNIX must be able to conduct "on-the-fly" transformations of all of the projections supported by VPF in support of visual displays. Other operational and user-interface components must change substantially to incorporate this difference in displaying data sources. VPFVIEW functions that will undergo expansion or modification include theme creation, feature selection list specification, text reporting, the save selected data function, map display, view manipulation, Libref coverage display, and hard-copy creation.

Significant improvements to symbology will also be achieved in the VPFVIEW–UNIX version. The higher display resolution of the platform will be an obvious improvement over VPFVIEW–DOS. Colors will be extended to be able to access a full range of 16-bit Red, Green, Blue (RGB) color values. Polygon fill styles will incorporate custom fill patterns, and the user will be able to specify different line styles for outlines. Several new line symbols will be added to the set of supported line styles. Approximately twenty additional Mark 90 line symbols will be supported. Marker symbols will be extended to include a "hot spot" that will be centered on the geographic location instead of the current default center of the symbol. It will be possible to display text in a variety of faces, styles, and sizes, using any of the fonts supported by the X Window System. Marker symbols and text will be scaled down when zooming out to reduce display clutter. Each view will be able to specify a custom symbology set location, upon creation.

Chapter 3. Phase II—DCW Database Production and Quality Assurance

3.1 Introduction

DCW database production was one of the main tasks for the DCW project, and as expected it claimed the largest portion of the project's resources. The production effort included developing both the GIS database and standard procedures for GIS database production. The production procedures were developed during the first year of the project as a part of the activities of the prototyping and design phase. Prototypes were developed during this period to explore the methodologies and standard procedures that were later implemented in production. The second year of the project focused on full-scale production. Full-scale production started after Prototype 4 in September of 1990 and continued until April 1992. A set of SOPs was developed as a technical guide for production. The SOPs were modified and improved throughout the duration of the project.

Source data were drawn from 270 ONCs and six JNCs. Because of the number of charts and the amount of data on each, a production plan encompassing production procedures and logistics, facilities, staffing, hardware, software, and quality control was created and implemented.

3.2 Production Management

The production of the DCW database was exceptionally labor intensive. Effective management practices were necessary to effectively control DCW production.

3.2.1 Production Staffing

Production staffing levels were analyzed periodically and adjusted to meet the schedule during production. Staffing was augmented as production warranted; about fifty personnel worked full time on production during the production peak. Two production shifts were implemented to permit interactive production equipment to be fully utilized. In addition, production batch processing was typically executed during the third shift.

3.2.2 Monitoring Program Status

To assist project management in monitoring the status of database production, a Spatial Project Tracking System (SPTS) was implemented. SPTS is a tool that assists ESRI project management in determining completion rates for in-house production. It also is an accepted and approved component of ESRI's Management Control System, a system for tracking and reporting cost and schedule performance (Cost/Schedule Status Reports). SPTS can produce reports or maps describing a project's progress (percentage of completion) at any level of project organization, including: (1) overall project; (2) mapping automation module; (3) task; and (4) subtask. SPTS was utilized in the DCW project to monitor all aspects of the database

production process from map preparation through to the VPF data conversion process. Other management tracking tools such as dependency charting programs and DCW production floor tracking charts were also used to support production management.

3.3 Production Environment

Before full-scale production began, the production environment was prepared by acquiring necessary hardware and software, establishing naming conventions, developing the data dictionary, establishing production organization and methodology, and developing standard operating procedures.

Hardware and software requirements were carefully evaluated. The hardware available was assessed against the production schedule throughout the project. Hardware that incorporated the latest technology was acquired as necessary to ensure efficient data processing and configured to permit communication through the local area network. The latest version of ARC/INFO (5.0.1) available at production start-up was utilized extensively in the production process.

A variety of computer hardware was used for the project. The scanner used for the DCW database was a full-size optical scanner with a maximum resolution of 1,000 DPI. The DPI of the scanner is variable; most of the scanning of the DCW database was done at 400 to 500 DPI. The scanner is configured to a computer with an 80386 processor, which was used to store the digital raster file from the scanner. A commercial software package was used to vectorize the scanned raster data and to convert the vector data into the Data Exchange Format (DXF). The database development hardware consisted of a file server, nineteen workstations, three tape drives for data backup, ten digitizing boards, one electrostatic plotter, and two eight-color pen plotters. The hardware was configured into a local area network, allowing data to flow from the scanning/digitizing processors to each workstation. The hardware and associated local area network configuration were specifically assigned to the DCW project and were independent of all other hardware within ESRI. This hardware configuration ensured the effective use of equipment and allowed efficient data flow and processing.

3.4 Production Sequence

Seven production sets and a production sequence were identified for the DCW project. The production sets were organized on the basis of geographic area, and the sequence of the production sets was arranged according to DMA's preference for data availability. The sets and sequence were as follows:

- Set 1: Europe
- Set 2: Northern Asia
- Set 3: South America
- Set 4: Southern Asia
- Set 5: Australia
- Set 6: North America
- Set 7: Africa

3.5 Data Dictionary

To guide database automation, a data dictionary was created that reflected the DCW database design. Because of the introduction of new features in some regions that were not originally known to exist, the data dictionary was refined six times during the early phase of the production. Version 6 was finalized in April 1991. During the database automation process, every member of the production staff kept a copy of the data dictionary on hand for reference.

The DCW product utilized a feature coding system based on the symbology guide for the ONC charts. Neither the FACS coding system (from the Digital Production System, or DPS) nor the FACC coding system (from DIGEST) was used. This is because DMA did not direct FACC codes to be used for its VPF products until after the DCW was complete. This is a project sequencing problem that will be rectified in future editions of the DCW.

3.6 DCW Standard Operating Procedures

One of the primary objectives of developing the DCW was to establish standard operating procedures to guide database production and subsequent database maintenance. The development of SOPs was initiated during the production of Prototype 3, and a document describing the procedures used to automate the database layers was written. The document served not only to provide guidelines for the production staff, but also to establish standards for database maintenance.

The SOPs were written and issued in three parts. Part One described standard operating procedures for the production environment; it described naming conventions, the data dictionary structure, the production set up, and automation preparation. Part Two described the standard operating procedures and gave detailed instructions for data layer processing in terms of creating clean, topologically correct ARC/INFO layers and for assigning feature attributes. Part Three, which was prepared upon the completion of separate convertor documentation, consisted of documentation for advanced processing steps, specifically edge matching and tiling. Part Three also described the division of the thematic data layers into libraries based on the tiling scheme, the conversion of the data in ARC/INFO data format to VPF, the premastering process, and the division of the VPF data into geographic regions for CD–ROM mastering defined by the geographic organization study. The SOPs were fully developed through iteration procedures from the prototypes to full-scale production.

3.7 Production Organization and Methodology

During the period of peak production, the production team for the DCW project was composed of about fifty people working in four areas: map preparation, scanning/digitizing, data processing, and quality assurance. The staffing levels in these groups were monitored to achieve a steady flow of production. The production manager was in charge of all the production work and coordination with technical managers and production group leaders in all the areas. The production manager called a technical meeting once a week with technical managers and group leaders to find out the status of the work and whether any problems needed to be resolved.

Because of the large amount of work in data processing, two working shifts were organized. Each data processing working team was assigned three ONC/JNC map modules. For those three modules, each team was required to complete all basic data processing and attribute assignment. As a team finished one map it was assigned another. For both basic data processing and attribute assignment, 100 percent quality assurance efforts were performed to ensure that the quality of work would meet requirements. Attribute assignment could begin only after the basic data processing was complete and the QA staff determined the coverage to be clean and topologically correct.

3.8 Production Procedures

The production period consisted of ramp-up, full production, and ramp-down periods. Scanning and digitizing was initiated in September 1990 and all four DCW CD–ROMs were created in "proof" form by April 1992. During the period from May 1992 to August 1992, after all other production operations had been completed, DCW product packaging took place. Product packaging consisted of duplication, packaging, and shipment of 10,000 copies of the CD–ROMs (along with VPFVIEW software and user documentation) to government distribution points in Australia, Canada, the United Kingdom, and the United States. (See Appendix A for distribution center addresses.)

To increase the efficiency of the production and establish standard procedures in processing, more than 200 AMLs were developed and used in production. These AMLs were divided into the following categories: set-up before processing, basic data processing, attribution, edge matching, tiling, check-plot creation, and quality assurance. The AMLs contributed not only greater production efficiency but also helped make data consistent. The use of AMLs and the continuing development of additional AMLs during the production period resulted in a three-fold increase in production efficiency during the twenty months of production.

Preliminary production procedures for the DCW database automation were developed during the design and prototyping phase, especially during Prototypes 3 and 4. These production procedures were described in the DCW SOPs. Although detailed DCW production varied from layer to layer, in general, the DCW production process consisted of twelve production steps (exclusive of quality control operations, which will be described below in Section 3.9). These steps are listed below.

1. Photographic reproduction of negative separates
2. Map preparation
3. Scanning and digitizing
4. Basic processing and initial corrections
5. Attribute assignment
6. Annotation automation and final corrections
7. Transformation and edge matching
8. Tiling
9. Conversion to VPF
10. Premastering
11. Mastering
12. Packaging

3.8.1 Photographic Reproduction of Negative Separates

The primary source for the DCW product was the photographic negative feature separates of the ONC and JNC series in archive at the Defense Mapping Agency Aerospace Center (DMAAC) in St. Louis, Missouri. These separates were removed from archive by DMA staff and shipped to a subcontractor, GEONEX Chicago Aerial Survey of Des Plaines, Illinois for 1:1 photographic reproduction of frosted acetate positives from the negative source separates. A total of 2,100 negative separates were used as the source for DCW database development and were photographically reproduced in this manner. During reproduction, registration marks were photographically reproduced onto each separate, ensuring that the separates could be spatially registered during the digital processes that would follow. After reproduction, the positive frosted acetate separates were shipped to ESRI for further processing as described below, and the negative separates were returned to DMAAC.

3.8.2 Map Preparation

In preparation for digitizing and scanning, most of the positive frosted acetate separates underwent a "map preparation" process in which features already present were enhanced by drafting scanning aids onto the separates. The positive separates had many feature characteristics that were disadvantageous for scanning. During the map preparation process, these features were modified to improve scanning success. A list of features that were enhanced through manual drafting techniques is presented in Table 5.

Tasks within map preparation were defined during the prototyping process based on a resource utilization analysis also conducted during prototyping. This resource analysis had shown that personnel resources would be more effectively spent conducting these manual map preparation processes before scanning rather than conducting additional, costly interactive editing after the scanning process.

An independent QC check for the map/data preparation was performed by QC staff to ensure that activities of the map preparation department met requirements for scanning, digitizing, and later processing. These QC steps will be described further in Section 3.9.

3.8.3 Scanning and Digitizing

Most thematic layers present in the DCW were scanned. Layers automated through digitizing were usually point layers, such as elevation points or cultural landmark points. During scanning, each frosted acetate separate released from the map preparation department was fed through an optical platform scanner. The scanner electronically captured an x,y coordinate grid of positions on the separate in raster format. Since the film separates were black-and-white, all rasters in the grid were either "on" or "off." The rasters that were "on/black" represented a gridded depiction of the features present on a particular separate. To achieve the DCW line accuracy requirements, scanner resolution was typically set at 400 dots per inch (DPI), although many dense separates (such as contour separates) were scanned at 500 DPI. No DCW data were scanned at a higher resolution than 500 DPI.

The majority of separates were scanned at ESRI using a raster scanner in this manner. However, approximately 100 contour separates were automated by the subcontractor GEONEX Chicago Aerial Survey using an automation processor which employed line-following algorithms and thus skipped the vectorization processes described below.

Table 5. Enhancements Completed During Map Preparation

Feature/Symbol	Enhancement
Intermittent streams	Solid lines were drafted through the discontinuous dot-dashed symbol to allow scanner recognition.
Other dashed symbols such as glacier extent lines or utility lines	Solid lines were drafted through the discontinuous symbols to allow recognition.
Swamps	On the separates, swamps were indicated through presentation of a regular pattern of point symbols. Boundaries around the swamp were drafted, and the scanner captured the extent of the swamp area as a polygon rather than capturing thousands of point symbols.
Other patterned area fills such as sandy areas, mangrove vegetation, fields, salt pans, or lava flows	Boundaries around these area fills were similarly drafted as polygons for scanner recognition.
Connection of roads, railroads, utility lines, contours, boundaries, and other linear features broken by text strings	On the paper chart lithographs for ONCs and JNCs, linear symbols are broken by text strings to improve readability of the text. When the chart is read by a human, the chart user mentally inserts the missing pieces of the linear feature into place. However, use of these features by GIS network algorithms requires that they be continuous. Therefore, during map preparation, these features were connected on the separates through manual drafting procedures.
Connection of roads and railroads through urban area polygons	On the ONCs and JNCs, roads and railroads are not connected through the yellow polygons representing urban areas. For 360 major cities of the world, independent map sources were utilized to compile generalized representations of the urban road networks through these cities during map preparation. For the remainder of cities represented as polygons, roads and railroads were connected through the cities to a single point and thus to each other under the assumption that road and railroad traffic would pass through the city in some manner. Thus, for these cities the correct geographic locations of the roads and railroads were not compiled even though network connectivity is maintained.
Point feature attribution coding	During map preparation, point features which appeared frequently and which had generic attributes such as "house," "farm," and so on, were assigned a code number during map preparation. These codes were then related to appropriate text string attributes during digitization.

A commercial software package was used to convert the scanned raster data to the vector data in DXF. The package utilized an algorithm that first calculated a "casing" or frame around the rasters representing a line and then calculated a centerline between the extremes of the casing. As noted in the prototyping discussion in Chapter 2, an algorithm of this form was determined to be superior in terms of linework data quality to so-called "pealing algorithms" found in many vectorization systems.

An advantage of the vectorization software that was used is that the casings that were created could be carried forward into the ARC/INFO editing process and used as a "back-cover" (or reference coverage) by data processors. The casing back-cover was used as a guide by the processors so that any movement of nodes or coordinates that they introduced could be confined to a movement within the casing.

Data exiting the vectorization software were in DXF format. The DXF data were next translated into the ARC/INFO data format using a specific ARC/INFO software utility. Four of the production steps described below were carried out within the ARC/INFO environment.

The ARC/INFO software was also used in digitizing. For digitizing, each source map manuscript was mounted on a large-format digitizing board and registered using assigned tics. The x,y coordinates locating feature information on the maps were electronically captured in vector format. Each feature in the coverage was coded with a unique identification code for later attribute assignment.

At the conclusion of the scanning/digitizing process, the ARC/INFO thematic coverage data were located in the file server in the production computer network for further processing. At this point, the QC department verified that scanning had been successful and that basic processing could proceed (see Section 3.9).

3.8.4 Basic Processing and Initial Corrections

The scanned data were processed to create a clean and topologically correct ARC/INFO coverage using ARC/INFO software. This basic processing step was the first of four steps conducted exclusively in the ARC/INFO production environment. The major interactive work performed by data processors during basic processing included:

- Conducting the "tic transformation" to register data from each chart separate to the data from all other separates for the given chart;
- Verifying that the Root-Mean-Square (RMS) errors for the transformation were within specification;
- Sorting data into appropriate DCW layers (there is not a one-to-one correspondence between ONC separates and DCW layers, so many data types were merged, separated, or otherwise reorganized);
- Deleting unnecessary dangles or random arcs (many of which were the result of scanned dust spots, scratches in the source separates, or failures of the vectorization process);
- Linking the broken lines that were supposed to be continuous;

- Cleaning the scanned module boundaries and deleting arcs outside the boundaries;
- Digitizing on-screen any features that were misidentified in the scanning and vectorization processes;
- Separating lines that were incorrectly joined during vectorization (for example, touching contours or double-line streams that had collapsed);
- Enhancing the line character of linework (for example, showing the correct angle of intersection of roads or railroads meeting at acute angles that had been incorrectly intersected during vectorization); and
- Creating line plots for verification by the QC department that basic processing was conducted appropriately.

Extensive ARC/INFO batch operations and both interactive and batch AMLs were used within this process to support the data processors. The digital map data were subjected to several rounds of electronic and visual checks, as specified in the QA program, to produce clean digital map sheets that accurately matched source manuscript maps (see Section 3.9).

3.8.5 Attribute Assignment

During attribute assignment, feature attributes were assigned to their associated cartographic features. Attribute data were captured using several methods. Some attribute data were entered in the digitizing process; thus, linework and attributes were captured simultaneously in this case.

The most common method of assigning attributes for scanned data was to code features directly on computer screen after clean and topologically correct layers were obtained in the basic processing step.

Sometimes AMLs were utilized to assign the codes to the corresponding features. For example, a "contour walking" algorithm was designed and implemented in AML. This algorithm allowed the processor to assign the contour attribute value to a single contour; the remaining (1,000-foot interval) contours were assigned through the algorithm. In a second example, inland water polygons (lakes and double-line rivers) were assigned an attribute of "water area" through a series of production processes and AMLs in which polygons were attributed through the use of a separate point coverage.

Certain attribute data already existed in digital format, such as aeronautical information from DMA's Digital Air Facilities Information File (DAFIF). These data were electronically transferred to the database format established in the physical database design before being subjected to quality assurance checks.

Again, at the end of this production step, significant QC activities were conducted and additional rounds of attribution were conducted if errors were identified. QC activities at this stage of the process relied on use of a composite plot generated on an electrostatic plotter (see Section 3.9).

3.8.6 Annotation Automation and Final Corrections

Attribute data that would appear within the DCW as text were entered into the database as annotation layers. Examples of annotation included place names, land use types, cultural names, and river names. The annotation labels were entered directly into the annotation layers as a graphic entry operation at the keyboards of workstations. To aid the entry operation, a raster display of the text was presented to the editor (from the scanner casing files). The editor was then required only to look directly at the screen and "overtype" the ASCII annotation data onto the raster image of the text. Entry of annotation was conducted both at ESRI and a subcontractor—GEOCODE of Eau Claire, Wisconsin. The annotation layers were subjected to visual quality control check to assure proper placement, size, and spelling of the map text. Diacritical marks were not entered for most text. However, text containing diacritical marks were sorted into layers separate from other text so that, in future editions of the DCW, diacritical marks can be added to the text.

Based on errors identified from a visual check of the composite plot, and other automated and visual checks, final ARC/INFO corrections were performed. All notes were reviewed by both the QC staff and the processing team leader for the layers of a particular map sheet to ensure that all errors identified through QC processes had been corrected by the processing staff.

3.8.7 Transformation and Edge Matching

Graphic edge matching is the process of connecting (by establishing one and only one common node) linear or polygonal features on a layer of a particular map sheet to their corresponding features on an adjacent map sheet.

Before edge matching could occur, all map sheets needed to be projected into a common coordinate system. The source ONC separates use a Lambert Conic projection based on a projection from the central meridian of each map sheet. Therefore, transformation information received from DMA was entered into a batch projection algorithm, and each sheet was projected to a common Plate Carree projection. The Plate Carree projection sets longitude equal to latitude so that plots of equal quantities of latitude and longitude (such as 1 degree by 1 degree) are square.

Graphic edge matching was performed for all source sheets (linear and polygon layers) of the DCW. In addition, attribute edge matching was performed throughout the DCW database to ensure that corresponding feature attributes were consistent along the boundaries of map sheets. Processors who conducted edge matching rigorously adhered to the following rule: the least accurate of the automated ONC/JNC features were physically moved to match the most accurate features. The accuracy information for each of the ONC and JNC sheets was provided by DMA. Code plots of the edge matched portion of all sheets were created in order to conduct a quality control check to verify that the same features along the sheet boundaries matched both graphically and by attributes.

3.8.8 Tiling

A fixed 5-by-5-degree tiling scheme was adopted for partitioning the DCW database into temporary libraries. Thus, the layers of each edge matched sheet were partitioned into 5-by-5-degree increments. Following partitioning, each layer for a map sheet was inserted into its appropriate library using a specifically written ARC/INFO AML. Next, a quality control

AML was run to check the correctness of the tiling results. The DISSOLVE function in ARC/INFO was then used to dissolve the edges of the map sheets out of the library, so that the library was discontinuous only at tile boundaries. (In the final product, tile boundaries do not affect data continuity, since cross-tile topology is created during the conversion to VPF.)

In addition to the quality AML noted above, visual plots of the data libraries both before and after tiling were created to ensure that all data were submitted into the libraries and that the file/directory references for the tiled data were correctly created.

3.8.9 Conversion to VPF

Additional major tasks consisted of converting the automated ONC and JNC data in ARC/INFO format to VPF and organizing the database into the final four DCW libraries. The conversion from ARC/INFO format to VPF format was based on two separate sets of programs—"set-up" procedures and "translate" programs.

A series of "set-up" AMLs (based on the ARC/INFO software) were first run to carry out a set of stand-alone processes on the ARC/INFO database. Some of these AMLs called C programs to build VPF winged-edge and cross-tile topology. Other AMLs built user-defined tables defined by the DCW product specification and thus were very specific to DCW and even to coverages within DCW. All set-up tools were run from within a single UNIX shell script called "SetupArcVPF." The set-up programs built a set of INFO program files known collectively as the "conversion interface format." This format was documented in the ARC/INFO-to-VPF Converter Programmer Documentation.

After completion of the set-up routines and creation of the files in the interface format, the translator was run as a batch program. The translator is a fixed set of C routines that carry out the final translation from the interface format to VPF tables. Since this software operated from a defined input format, it does not change for any VPF product. The translator converted both INFO files from the set-up procedures and additional ASCII files that were translated into VPF metadata. Metadata is the descriptive information that VPF carries in header tables to inform users or applications software about the contents of the database.

A quality check was performed after each of the two sets of procedures. During the first round of quality control (after running the "set-up" AML), feature tables were checked to verify the correctness of records, and feature counts were conducted to ensure that all features had successfully been translated. If these QC processes identified any errors, the set-up procedures were rerun. After running the translator, the VPFVIEW program was utilized to allow the visual verification of graphic displays of the converted data on the screen. In addition, a batch program entitled VPFVERIF was then run to check the relationships between the feature tables and VPF data primitives and to ensure that all files could be correctly read. These QC checks were performed on every layer of the DCW database.

The other major task involved in this post-processing production stage was organizing the database so that data were appropriately placed onto the four DCW CD-ROMs. Based on the DCW geographic organization study, the globe was organized on the CD-ROMs into four geographic areas: North America, Europe/Northern Asia, South America/Africa/Antarctica, and Southern Asia/Australia. Several processes were conducted to organize the DCW database onto the four libraries with appropriate overlap areas as defined by the geographic organization study.

3.8.10 Premastering

Premastering involved the preparation of data for CD–ROM replication. It included preparing tapes for shipment to the premastering subcontractor—GEOVISION of Norcross, Georgia—and a series of activities conducted at GEOVISION involving the receipt, handling, and processing of data and its ultimate output to magnetic tape for transmission to the replicating facility.

After completion of the ARC/INFO-to-VPF conversion process described above, a UNIX shell program was executed. The UNIX shell called a series of subroutines that conduct the following process:

- Searches for and deletes empty directories;
- Creates batch files that can be used to
  - Create all necessary directories for the DOS premastering partition, and
  - Include all directories and files in the tape writing process;
- Creates a batch file that can be used to:
  - Create all necessary directories for the ISO 9660 premastering partition, and
  - Copy data from the DOS premastering partition to the ISO 9660 partition.

Two of the three batch files were then used at GEOVISION during the additional premastering processes described below. These file/directory handling processes described above seem rather simple until one realizes that the DCW is contained in over 150,000 files. Thus, the file handling operations needed to be automated to the greatest extent possible. Upon completion of the shell program, all data and batch files were written to magnetic tape using the UNIX TAR tape writing utility, and the tapes were shipped to GEOVISION.

At GEOVISION, commercial CD publishing software was utilized to permit ISO 9660-compatible CD–ROM data preparation, premastering and master manufacturing tape generation. Tasks involved in this process included:

- System configuration
- Creation of the DOS directory structure based on using the results of the shell program described above

- Transfer of data from the magnetic tapes to the DOS partition
- Verification that the data in the DOS partition matches that of the magnetic tape
- Creation of the initial ISO 9660 partition using DOS-like commands to organize files and directories
- Creation of the ISO 9660 directory structure and transfer of the data into the ISO 9660 partition based on using the results of the shell program described above
- Organization of the ISO 9660 directories and files by exact physical block location and size
- Simulation of the performance of the CD–ROM utilizing the magnetic media partition
- Generation of the master manufacturing tape, and
- Shipment of the master manufacturing tape to the mastering vendor.

3.8.11 Mastering

CD–ROM mastering was conducted at the Disc Manufacturing, Inc. (DMI), production facility in Huntsville, Alabama. In general, CD–ROM mastering steps consisted of the following activities:

- Laser beam recording by writing the bit stream from the master manufacturing tape onto a flat glass substrate coated with a thin layer of photosensitive material
- Monitoring the glass master creation with laser quality control devices
- Electroplating a nickel shell onto the glass master to create the "father disc"
- Generating a "family" of nickel stampers through electroplating
- Preparing a "stamper" and inserting it into the CD–ROM press
- Pressing (or molding) the disc onto raw polycarbonate
- Metalizing the molded disc with an aluminum reflective film
- Lacquering the metalized disc with a protective varnish by dripping the lacquer onto the rotating disc
- Conducting automated quality control operations of the molding/coating processes
- Printing the disc label directly onto the protective lacquer
- Conducting quality inspections of the disc label

- Packaging the discs into their jewel cases (in the case of the DCW, one jewel case containing the four CD–ROMs for each DCW set)
- Inserting the disc booklet into the jewel case
- Conducting visual quality control of the packaging process
- Shrink-wrapping the jewel case, and
- Shipping the CD–ROMs to the assembly vendor.

3.8.12 Packaging

The preceding eleven production steps were all conducted during the period from September 1990 until April 1992. By April 1992, 150 "proof" copies of each of the four DCW CD–ROMs had been created and reviewed by DMA. DCW packaging activities occurred during the period from May 1992 until August 1992. During the DCW product packaging activity, the four preliminary CD–ROMs were duplicated (10,000 copies of each), packaged (along with 10,000 copies of the VPFVIEW software and user documentation), and shipped to government distribution points in Canada, the United Kingdom, the United States, and Australia.

Packaging elements consisted of two documents, six floppy disks, four CD–ROMs, and the boxes necessary to contain them. Package design took place primarily during the latter half of 1991 and resulted in the DCW Package Design study. Packaging elements and subelements are listed here:

- *VPFVIEW 1.0 Users Manual for the DCW*, as follows:
  - — Color cover
  - — Text
  - — Bar code
- *DOS Installation Instructions for the DCW*, as follows:
  - — Black and white cover
  - — Text
- Floppy disks containing VPFVIEW source software, VPFVIEW executable software, and VPFVIEW views, as follows:
  - — Three 3.5-inch and three 5.25-inch floppy disks
  - — Disk envelope and label
  - — Three 3.5-inch and three 5.25-inch disk labels
  - — Six bar codes

- CD–ROMs containing DCW data, as follows:
  - — Four CD–ROMs
  - — One jewel case containing the four CD–ROMs
  - — Jewel case front cover
  - — Jewel case back cover
  - — Insert booklet
- Containers, as follows:
  - — Inner container (light cardboard box enclosed by a sleeve printed in color)
  - — Outer container (heavy, white corrugated cardboard mailer—tuck top style)
  - — Outer container label/bar code
  - — Carton containing ten mailers
  - — Pallet set containing thirty-two cartons

Prior to DCW product assembly, all packaging elements were printed or otherwise duplicated. CD–ROMs were stamped, checked, and assembled into jewel cases at DMI. All paper materials were printed at NORSTAR Printing Corporation using designs developed into camera-ready copy at ESRI. The six floppy disk masters were created at ESRI. They were duplicated at IPC Software Corporation. Disk duplication quality control operations at IPC Software included verifying the absence of over 150 known software viruses and reading back data from all disks that were duplicated.

After 10,000 copies of all DCW packaging elements were created, IPC Software conducted product assembly of all packages, including assembly into cartons and pallet sets. Pallet sets were shipped to ESRI for final inspection, and then reshipped to government distribution points. All packaging activities from CD–ROM duplication to shipping were accomplished over a period of fifteen weeks.

3.9 Quality Assurance

A Quality Assurance (QA) plan was developed and implemented on the DCW project to ensure that all products conform to the detailed specifications for content and accuracy agreed upon by the participating agencies. DCW quality assurance activities were identified as belonging to four overlapping areas: (1) activities supporting effective QA for the project, (2) software development, (3) database development, and (4) CD–ROM premastering and mastering. The first area was a pivotal component of the DCW project infrastructure; it controlled the inputs and outputs of the product development process and ensured the quality of the final integrated project deliverables. The other three areas were concerned with placing controls on specific product development activities. Of the three, quality assurance efforts focused primarily on database development, since this portion of the project was the most complex and labor intensive.

3.9.1 Activities Supporting Quality Assurance

Some QA activities supported a number of aspects of the project and were product independent. Activities in this area consisted of well-defined procedures for the management of materials used in the production and delivery process, including the receipt and transfer of

materials, internal tracking techniques for determining the status of the project and the position of production units within the process, product archiving, QA evaluation of subcontractor activities, the review of in-house staff training, and test procedures for peripheral hardware. These procedures provided effective and efficient QA for DCW production activities both at the main production facility at ESRI and at subcontractor establishments outside.

3.9.2 Software Development Quality Assurance

Software QA activities were performed to ensure that all project software met the DCW requirements, worked soundly, and was error free.

Two categories of software were identified for the DCW project: (1) application software, and (2) production and quality control software. Each software had distinct QA requirements. Application software refers to the VPFVIEW software provided with the product. This software had a sophisticated user interface and was highly integrated. Production and quality control software refers to software that was developed specifically to assist in the database development effort. Within the ESRI production environment, the production and quality control software consisted of macro-level programs for performing specific tasks, such as basic data processing or plot generation.

For the quality assurance of application software, a full regime of unit, integration, and functional testing was performed. All testing phases were guided by detailed plans for performing the work. Unit testing was performed by ESRI staff. Integration testing was performed by Loral Defense Systems—Akron (LDSA). Functional testing was performed jointly by ESRI, LDSA, and DMA. (See Section 2.5 for a more detailed description of VPFVIEW testing activities.)

To make sure that the production and quality control software met DCW production requirements, a Production System Software Review was conducted before the software was placed under configuration management. The DCW production software consisted of a set of independent macro-level programs written in AML and INFO. The programs were developed to handle the high-volume data processing demands of DCW production. The quality of output was ensured through the successful generation of the prototypes and maintained through database production and QA feedback during implementation.

The Production System Software Review, which was dedicated to software issues and to the creation of a unified library of routines to form the basis of the production effort, was conducted to ensure the quality of the production routines. The review identified standards for internal and external documentation, the functioning of the user interface, and operational consistency.

3.9.3 Database Development Quality Assurance

Database development was the most complex portion of the DCW project from a quality assurance perspective. It involved a large number of staff members performing a myriad of activities on a demanding schedule. The quality of the product was maintained through two primary mechanisms: (1) detailed data quality inspections at key junctures in the production process, and (2) the standardization of the activities performed by processing staff members.

The DCW database development process can be viewed as consisting of six primary activities: (1) map/data preparation, (2) map data scanning/digitizing, (3) basic data processing, (4) composite plot development, (5) edge matching and tiling verification, and (6) VPF conversion and data finalization. Quality control work focused primarily on these activities. (These activities correspond to production steps 2 through 9 under Section 3.8.)

3.9.3.1 Quality Control for Map Preparation

Map preparation QC for the frosted acetate separates prior to scanning or digitizing included checking the accuracy of registration tics, adding logical connectors to continue the linear features broken by text or other features, checking the consistency of the drafting symbols used by the map preparer, checking the connectivity of the lines, and so forth.

3.9.3.2 Quality Control for Scanning and Digitizing

Scanning and digitizing consisted of creating vector representations of ONC/JNC features. The vector representatives were created in one of two ways, depending on the feature types to be automated. In general, thematic data separates bearing linear features were scanned and those bearing point features were digitized. Scanning and digitizing had distinct quality assurance requirements.

The scanning process had two primary steps: scanning and vectorization. After the scanned raster data were converted to vector data using vectorization software, QC was performed on sample areas to assess the adequacy of the vectorization parameters, and the vector data were reviewed on the screen to ensure the process had produced vector data of the highest quality. Another QC procedure that was performed was to compare the pretransfer and posttransfer file sizes for consistency. Then the vector data were transferred to ARC/INFO format for processing and the file sizes were checked again for consistency. Vector data were edited in the ARC/INFO environment. After initial processing in the ARC/INFO environment, the processed data were plotted out at 1:1 scale to the source sheet and sent to the QC staff for cartographic accuracy checking.

The digitizing process began with mounting the frosted acetate separate on a digitizing board. The separate was then registered to a master set of registration points using the affine transformation. Acceptable minimum root-mean-square (RMS) error tolerance was 0.004 inch. In instances where this tolerance could not be achieved, the separate was taken down and compared to the projection separate (the sheet standard) to determine if the tics were properly aligned. Any tics found to be offset were eliminated from the projection set. In some instances, the separates had become distorted as the result of the environmental changes, in which case an RMS value larger than the set tolerance was unavoidable. RMS errors were recorded in the digitizing log. After the digitizing, the data were plotted out at 1:1 scale to the source sheet and made available to the QC staff for cartographic accuracy checking.

3.9.3.3 Quality Control for Basic Data Processing

Basic processing was the process of creating topologically correct and positionally accurate line work. Quality control for this process was achieved through (1) automatic checking and (2) manual checking.

Automatic checking entailed using the utilities in ARC/INFO or specifically written AMLs to verify the topological structure, to check the polygons for labeling errors, to check the coverage for precision, to assess error tolerance values, and so forth.

To permit manual checking, the processed data were plotted out, overlaid on the original frosted acetate manuscripts against an illumination source, and reviewed for deviations from the source map. The purpose of this inspection was to verify cartographic accuracy, identify topology violations, and verify the completeness of the data. Specifically designed marks were used to denote different types of errors to guide the data correction process.

After the QC checks were finished, the check plots were sent back to the processing staff for corrections. This cyclical process continued until all known errors were resolved. Initial reviews were exhaustive; subsequent reviews focused on verifying that previous corrections were performed properly.

3.9.3.4 Quality Control for Attribute Assignment

During attribute coding, cartographic features were assigned the attribute code values defined by the data dictionary. Attribute code accuracy was tested by using a combination of automated and manual techniques. The automated attribute QC tests were performed first. They consisted of valid code checks, code consistency checks, frequency checks, INFO item checks, and others. The resulting automated attribute QC error listings were used by the QC staff to thoroughly review the attribute codings.

As a manual check, plots were made after the coding process was completed and sent to the QC staff for quality checking. The quality checking was facilitated by the use of color coding and special symbols for the plots. Independent inspections called attribute code reviews were made of 100 percent of the feature attribute codes. An iterative process of QC checking was conducted for attribute coding until all known errors were resolved.

3.9.3.5 Quality Control for Composite Plots

After the finalization of the line work and attribute coding, a composite plot of all layers was produced on a color electrostatic plotter. This plot was reviewed against the original printed map for the proper relative positioning of features, and for data omissions. Statistics on the data were generated at this time as well, including descriptions of data attribute fields, frequency counts of data attributes, and an ARC DESCRIBE listing providing information on number of features, topology status, data extent, coverage precisions, and edit status.

3.9.3.6 Quality Control for Edge Matching and Tiling

A transformation process was conducted which consisted of joining individual production modules (ONC sheets) into a seamless database and then partitioning the database into tiles. This entailed transforming the data into real-world coordinates, inverse projecting the data into decimal degree coordinates (Platte Carree projection), edge matching the individual tiles, and merging and partitioning the data into tiles using Map LIBRARIAN program of ARC/INFO.

After the data were projected into decimal degree coordinates, a plot was made of registration tics with identifiers for review by the quality control staff to ensure that coordinate transformations and projections on all layers had been performed correctly.

A series of plots covering only map sheet edges were produced for edge matching QC. The QC staff then manually indicated links between features on adjacent charts. When mismatches were identified, the QC staff used the more accurate sheet as the criterion. Corrections were then made by the processing staff in an ARCEDIT environment; the least accurate features were moved to match the positions of the most accurate features.

After sheet merging and tile partitioning, a set of tiles was arbitrarily selected and a series of diagnostic statistics were run on them; a visual review was performed, and a listing of selected records from the primary attribute tables was generated. This information was compared later to the same information after the data were converted to VPF.

3.9.3.7 Quality Control for VPF Conversion and Data Finalization

Once the database was completed in ARC/INFO, it was converted to VPF and restructured according to the CD-ROM geographic organization. At this time, the primary data quality concerns were completeness and correctness of the conversion process.

Conversion software converted the ARC/INFO data into VPF format on a tile-by-tile basis, renamed individual files and directories, and organized the data in a manner that was consistent with the DCW product specification. In addition, all data were visually reviewed in VPFVIEW for completeness and to verify that attribute tables were correct and intact. Automated checks were also run to verify completeness and the integrity of the internal data structure. These automated checks included feature count comparisons, as well as tests for proper relationships between feature table records and primitives, and topological relationships. Taken together, these processes served to verify completeness and correctness in a comprehensive fashion. This process was repeated until all known errors were corrected.

3.9.4 Quality Control for CD-ROM Production

The CD-ROM manufacturing process consisted of two primary tasks: (1) premastering and (2) mastering. Quality assurance for each task entailed different activities.

3.9.4.1 Quality Control for CD-ROM Premastering

Quality control for CD-ROM premastering focused on a series of data verifications, including the completion of transfer tape transmittal forms for the nine-track tape, transfer tape QC reports, and the completion of tape transmittal forms for the premastering tape.

The first step in premastering was to transmit the digital data on nine-track tape from ESRI to the premastering subcontractor (GEOVISION, Inc.). ESRI used standard digital tape transmittal procedures and transfer tape transmittal forms in documenting the process. The recorded information included file names, byte counts, and file sequence/ID numbers for all files, which were organized by CD-ROM disc number.

Next, GEOVISION loaded the data from tape and compared what was received from ESRI with the description on the transfer tape transmittal form. The result of this process was a transfer tape QC report. The report listed any discrepancies found and corrective actions taken and indicated any further ESRI action that might be necessary.

GEOVISION reformatted the data and conducted a series of tests in which the behavior of the data on the CD–ROM media was simulated. After the tests were successfully concluded, GEOVISION transferred the data to the mastering subcontractor (Disc Manufacturing, Inc., or DMI) on a master manufacturing tape. Prior to this step, a premaster tape transmittal form was completed, documenting the data characteristics at the time of shipment, and sent to ESRI for review.

Upon receipt of the data, DMI initiated a disc mastering process. DMI also provided GEOVISION with a premastering tape vendor QC report of the data characteristics. A premaster tape vendor verification report was also generated by GEOVISION after an extensive comparison of data characteristics was completed.

3.9.4.2 Quality Control for CD–ROM Mastering

CD–ROM mastering was the production of master "molds." For mastering, the primary objective of quality control was to monitor the physical characteristics of the discs. After producing the first set of CD–ROMs, DMI provided ESRI with a stamper quality control report. The report consisted of the results of internal tests conducted on the model used to press the CD–ROM discs. The next step connected with CD–ROM mastering was to test the discs. The results of these tests were documented in a test disc and stamper verification report which presented the level of the physical and data integrity for ESRI's approval or disapproval. The functional testing of the discs was also undertaken at this time. At ESRI, the functional testing concentrated on data access through the application software; at GEOVISION, it concentrated on disc readability on a variety of platforms. Discrepancies found were listed in a QC report, and corrective action was taken.

Following acceptance of the test product, ESRI gave DMI permission to proceed with CD–ROM production. The final disc production report and QC report were completed after the final test was conducted on the actual CD–ROM production run.

3.10 Desert Shield/Desert Storm Support

3.10.1 Introduction/Objective

In August of 1990, DMA asked ESRI to provide GIS support for the U.S. government. This support consisted of data conversion of existing City Graphic (CG), JOG, Tactical Pilotage Chart (TPC), and ONCs of the Persian Gulf region. The ONC effort was performed as a part of the overall DCW project. The scales of the source data are 1:12,500 and 1:25,000 for the CGs, 1:250,000 for the JOG, 1:500,000 for the TPC, and 1:1,000,000 for the ONCs.

The TPC and ONC databases were automated in accordance with the DCW database design. The CG and JOG databases were automated in accordance with a database design supplied by DMA. This database design used the FACS coding system as established in DMA's Digital Production System.

3.10.2 History

In August of 1990, DMA asked ESRI to provide GIS support for the U.S. government's participation in Operation Desert Shield. ESRI began converting CG charts under the DCW

contract at the beginning of September 1990. The conversion schedule was very short and did not allow sufficient time to edge match the ARC/INFO databases. All data layers were captured and delivered in early October.

The JOG conversion effort began in October with a pilot consisting of two JOG charts. All data were captured following FACS guidelines. The pilot also investigated the feasibility of using automation subcontractors in order to meet the rigorous production schedule. The JOG conversion project was completed in March 1991. The TPC effort began in October and was delivered in December 1991, and the ONC effort was incorporated into the ongoing DCW project.

3.10.3 Production

This section describes production issues concerning the design and production procedures for the product.

3.10.3.1 City Graphics Conversion

In late August 1990, ESRI received notification that seven City Graphic charts needed to be converted to ARC/INFO format. At that time, two DMA representatives came to ESRI to review the proposed database design and to resolve any production questions. The data sources were photographic positive films. Each film positive contained different feature types. Transportation data appeared on multiple film separates. Some transportation line features for the Kuwait City charts were generalized as a result of the nature of the data source. DMA and ESRI staff determined that the integration of these separates was best performed by drafting all lines onto new film manuscripts. These manuscripts were scanned and then processed. Three 1:12,500 CG charts for Kuwait City and four 1:25,000 CG charts for Baghdad were captured in ARC/INFO.

Each separate was scanned and converted into vector format as a single coverage. All coverages were transformed using one set of master tics. Each coverage was edited and coded according to data sources. After basic processing and coding, each production coverage was separated into the ten layers specified in the database design. These final coverages were edge matched, transformed, and then projected to decimal degrees. Because of the two different scales, Kuwait City roads were captured as parallel lines with a median polygon in between, whereas Baghdad roads were captured as single lines. All Kuwait City buildings were captured as polygons, whereas Baghdad buildings were captured as points. The Kuwait City data did not contain tinted urban areas; urban areas for Baghdad were captured as polygons.

The database design was based on the Feature Attribute Coding Dictionary (FACD). Briefly, the FACD separates all features into ten layers: CUL1 (culture 1), CUL2 (culture 2), TRNS (transportation), VEG (vegetation), ELEV (elevation), COMM (communication), PHYS (physiography), HYDR (hydrography), GEN (general), and BND (boundaries). All layers were converted except ELEV (Elevation). Each feature attribute table contains only the record ID and the FACS code of the feature. All attributes for a given coverage were split into different tables based on their FACS codes. This meant that each table for a particular coverage needed a different set of attributes.

Many of the features in the City Graphic data sets were not fully supported by FACS or not clearly described in the digital City Graphic product specification; these features were coded

with nonstandard FACS codes or attributes. Many features could not be interpreted from the data sources and therefore could not be clearly defined by FACS. These instances were fully reviewed with DMA and documented.

3.10.3.2 Joint Operations Graphic Conversion

In October of 1990, ESRI was notified that JOG charts needed to be converted to ARC/INFO format. The data source was photographic positive films. Each film positive contained different feature types. As specified in the database design, six JOGs were converted into ARC/INFO format with all layers, except elevation. Twenty-two JOGs were converted with only the following features: all roads (including tracks), hydrography (except intermittent drainage, swamps, or land subject to inundation), population point and polygons, and international boundaries.

Each separate was scanned and converted into vector format as a single coverage. All coverages were transformed using one set of master tics. Each coverage was edited and coded according to data sources. The database design used for the JOG conversion was essentially the same as that used for City Graphic conversion.

Many of the features in the JOG data sets were not fully supported by FACS or not clearly described in the digital JOG product specification; these features were coded with nonstandard FACS codes or attributes. Many features could not be interpreted from the data sources and therefore could not be clearly defined by FACS. These instances were fully reviewed with DMA and documented.

3.10.3.3 Tactical Pilotage Chart and Operational Navigation Chart Conversion

In October of 1990, ESRI received notification that three TPC charts and one ONC needed to be converted to ARC/INFO format. The data source was photographic positive films. Each film positive contained different feature types. A decision was made by DMA to convert the TPC charts using the database design being developed for the ONCs for the DCW database. This database design included the following layers:

- Cultural/political data layers: political/oceans, populated place, railroads, roads, and utilities.
- Surface information data layers: drainage, supplemental drainage hypsography, supplemental hypsography, land cover, ocean feature, and physiography.
- Aeronautical information data layers: aeronautical, cultural landmarks, transportation structure, and vegetation.
- Data quality information data layer: data quality.

These coverages were created and processed using the SOPs from the DCW production project.

Chapter 4. New Vector Product Format Products

4.1 Digital Nautical Chart

The DCW project set the stage for a series of additional ESRI projects for the Defense Mapping Agency: the Digital Nautical Chart (DNC) project and the Vector Smart Map (VSM) project. This work is designed to meet the growing demand for military GIS analysis using data in VPF.

4.1.1 Introduction

In an additional application of the VPF standard, ESRI is producing a prototype database formatted in VPF that will be used to support computerized marine navigation. The DNC project is a pilot program that will provide the U.S. Navy and the U.S. Coast Guard with digital hydrographic and topographic data on CD-ROM for the Norfolk, Virginia, and New York City harbor areas. These prototype databases will contain up to fourteen data layers, including port facilities, aids to navigation, limits, obstructions, and hydrography.

4.1.2 DNC Project Objectives

Four objectives were identified for the DNC project.

- To provide proof of concept for a digital, geographically based, nautical chart display and navigation system.
- To provide an opportunity for evaluating the DNC system through the use of prototypes.
- To conduct tests on site that simulate actual working conditions.
- To demonstrate GIS database applications.

4.1.3 Design Overview

The intention of the project was to create a series of DNC prototype databases structured in VPF. For each DNC prototype, DMA is providing a product specification that describes the feature content, accuracy, and data format. The FACC coding scheme is being used to code the features and attributes in the most recent prototype of the DNC.

4.1.4 DNC Database Content

The DNC database is divided into four libraries based on the type and scale of the source charts.

- The General library at a scale of 1:500,000 or smaller
- The Coastal library at a scale of 1:75,000–1:500,000
- The Approach library at a scale of 1:25,000–1:100,000
- The Harbor library at a scale of 1:10,000–1:50,000

Up to fourteen thematic coverages were identified for each library: Cultural Landmarks, Earth Cover, Inland Waterways, Land Cover, Relief, Port Facilities, Aids to Navigation, Obstructions, Hydrography, Environment, General Information Limits, Caution Limits, Avoidance Limits, and Navigation Limits.

4.1.5 Production

The database for the DNC prototypes consists of information extracted from nautical charts published by the National Ocean Service (NOS). In general, the production of the digital DNC database from hard copy source requires the same processes as used for the DCW:

- Chart preparation (review for content and quality)
- Scanning and digitizing (convert the chart data to digital data)
- Cartographic editing (check the data for positional accuracy, eliminate errors, and build topology)
- Attribute coding (code features with their proper attributes in accordance with the product specification)
- Finalization (edge match and tile)
- Convert to VPF
- Distribute data on CD–ROM in VPF.

4.1.6 Development Status

The DNC project is being developed in four prototypes, with each prototype involving a larger and more complex data set.

4.1.6.1 Prototype 1A: Floppy Disk Data Sampler

Prototype 1A consisted of 5-by-5-minute subsets of the data digitized for DCW Prototypes 2 and 3. DCW TYPE and STATUS codes were used to code the features and attributes. The automated data were converted to VPF and delivered to DMA on floppy disk in November 1991.

4.1.6.2 Prototype 1B: Magnetic Tape Data Sampler

Prototype 1B consisted of data from NOS Chart 12245 that were digitized for DCW Prototypes 2 and 3. Feature attributes were coded in accordance with the FACS attribute coding scheme. The data were converted to VPF data structure and delivered to DMA on magnetic tape in January 1992.

4.1.6.3 Prototype 2: CD–ROM Data Sampler

Prototype 2 consists of data extracted from six NOS charts of the Norfolk, Virginia, area. The feature attributes were assigned in accordance with FACS. The data were converted to VPF and delivered to DMA on CD–ROM in June 1992.

4.1.6.4 Prototype 3: CD–ROM Data Sampler in FACC

Prototype 3 will include five additional charts from the New York harbor area in addition to the six NOS charts of the Norfolk, Virginia, area. All features will be assigned with the codes in accordance with FACC. The data will be converted to VPF, with multiple feature classes and join tables. CD–ROM will be used as the storage medium. Prototype 3 will be delivered to DMA in December 1992.

4.1.7 Source Materials

DNC Prototype 2 was populated with the feature content of six NOS charts from the Norfolk, Virginia, area.

Chart Number	Scale	Chart Type
12200	1:419,706	Coastal
12207	1:80,000	Approach
12221	1:80,000	Approach
12222	1:40,000	Harbor
12245	1:20,000	Harbor
12254	1:20,000	Harbor

DNC Prototype 3 will include five additional charts from the New York harbor area:

Chart Number	Scale	Chart Type
13003	1:1,200,000	General
12300	1:400,000	Coastal
12327	1:40,000	Harbor
12339	1:10,000	Harbor
12366	1:20,000	Harbor

4.1.8 Summary

If, in the future, the requirements of ship navigation can be met by using VPF databases published on CD-ROM instead of by using the traditional paper chart, significant onboard space savings will be realized. More important, because VPF digital databases will be able to be updated more frequently than paper charts, they will provide more current information about naval hazards and, thus, safer navigation. In addition, DNC data may permit the implementation of a concept called "interactive navigation." Interactive navigation would allow navigators to chart course after evaluating a number of variables, including depth, navigation limits, and obstructions.

4.2 VSM Development

4.2.1 Project Objective and Scope

To support the establishment of the VPF standard, DMA tasked ESRI to develop product specifications and prototype databases for a third VPF digital product series for GIS applications. The product specifications and prototype databases described below are designed to support the VSM program. The product specifications will reflect the current VPF standard.

The VSM project will entail the production of two databases. A high-resolution database will contain data converted from high-resolution sources, such as sources at 1:50,000 or 1:100,000 scale. A medium-resolution database will contain data converted from medium-resolution sources, such as the 1:250,000-scale Joint Operations Graphic charts (JOGs).

Two prototypes of each database are to be developed. The first prototype will use the Feature Attribute Coding System (FACS). A second prototype has been proposed to implement the Feature Attribute Coding Catalogue (FACC).

4.2.2 Project History

The VSM project began in December 1991 as a modification of the basic DCW contract. At DMA request, ESRI considered several design options, including using the digital JOG as a data source. The design was presented to DMA in February 1992, when the following issues were discussed: the thematic layers to be included in the database; the features to be included in the databases; the attributes and attribute values for each feature; and the implementation of the VPF standard in the VSM design.

A draft of the product specification was submitted to DMA in July 1992. The medium-resolution and high-resolution data were digitized from government-furnished film separates.

4.2.3 Characteristics of Database Designs and Product Specifications

The design for the two VSM databases is based on the VPF standard. Mandatory VPF tables and reference libraries (one per database) are carried at the database level. One library reference coverage and one tile reference coverage for each library are carried at the library level, as are other mandatory VPF tables.

The design for the medium-resolution and the high-resolution databases are identical at the library level. At the coverage level, the differences between the databases reflect the differences between the features and their attributes. These differences are also reflected in the different feature classes in the medium- and high-resolution libraries.

The main portions of the VSM product specifications describe the implementation of the VPF standard at the database level. Appendixes contain the tables for the high- and medium-resolution libraries.

Appendix A. DCW Availability

In the United States, Latin America, Asia, and Africa:

U.S. Geological Survey
ESIC—Open File Section
Box 25286
Federal Center
Mail Stop 517
Denver, CO 80225
U.S.A.

Tel: (303) 236-7476

(U.S. Dept. of Defense users may contact:)

Defense Mapping Agency
Combat Support Center
Attn: PMSC/D-16
6001 MacArthur Blvd.
Bethesda, MD 20816-5001

Tel: (301) 227-5518

In Canada:

Products and Services Division
Surveys, Mapping, and Remote Sensing Sector
Energy, Mines and Resources Canada
615 Booth Street, Room 400
Ottawa, Ontario
CANADA K1A 0E4

Tel: (613) 995-2123
Fax: (613) 995-6001

(Defense users may contact:)

Directorate of Geographic Operations
National Defence Headquarters (NDHQ)
Surveys and Mapping Bldg.
Ottawa, Ontario
CANADA K1A 0K2

Tel: (613) 992-7666
Fax: (613) 996-3328

In Europe:

Chadwyck-Healey Ltd.
Cambridge Place
Cambridge CB2 1NR
UNITED KINGDOM

Tel: (0223) 311479
Fax: (0223) 66440

(Defense users may contact:)

Requirements Division
Geo Commitments Group
Elmwood Avenue
Feltham
Middlesex TW13 7AH
UNITED KINGDOM

Tel: (081) 890 3622 ext. 4134
Fax: (081) 890 3622 ext. 4148

In Australia:

The Manager
AUSMAP Data Unit
P.O. Box 2
BELCONNEN ACT 2617
Australia

(Defense users may contact:)

Directorate of Survey–Army
Campbell Park Offices
Building CP2-4-24
CAMPBELL ACT 2601
Australia

Appendix B. References

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Military Standard—Vector Product Format. 13 April 1992. MIL-STD-600006. Available from the Defense Printing Service, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

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Appendix C. Training

A training plan was prepared to transfer the technology of the VPF standard. The training plan provides for a combination of classroom instruction, audiovisual aids, demonstrations, and hands-on practice to demonstrate VPF concepts and design; automated routines for database transfer to VPF; and the system architecture of the VPFVIEW application software.

A modular approach was taken to the training plan. Each module is a self-contained unit with unique prerequisites and learning objectives that are to be met within the module. The modules can be tailored to the needs of those in the class. The training program focuses on training DMA staff, but the modularity of the training program will make it adaptable to other groups. The modules and courses are listed below.

Module 1—VPF Data Conversion and CD-ROM Premastering

Module 1 consists of two courses: the conversion of data to VPF, and the premastering of VPF data. Metadata generation and quality control for VPF data will also be discussed.

Course 1: Preparing and Converting a Database into VPF. The goal of this course is to train DMA personnel in the production procedures required to prepare a database for conversion to VPF, and the procedures required to convert a database to VPF.

Course 2: VPF Database Premastering. The goal of this course is to train DMA personnel in the production procedures required to generate complete premastering files from a VPF database, and give them insight into the premastering process. The course also reviews procedures for conducting the premastering process, including the preparation of a tape for delivery to a mastering vendor.

Module 2—Introduction to the VPF Standard and Concepts

The goal of this course is to provide a student with knowledge of the fundamental concepts and basic understanding of the data structures and use of vector product format. The discussions will include an overview of the VPF georelational model, including the meaning of data objects, data operations, and data rules for geographic data management, analysis, modeling, and display.

Module 3—Advanced VPF Training

Course 1: Advanced VPF Standard and Concepts. The goal of this course is to provide a student with a knowledge of advanced VPF concepts and use and manipulation of the data structures of vector product format.

Course 2: VPF Database Design. The goal of this course is to train students to design databases in VPF, and to create a VPF database design that may be generated from any other

GIS format that utilizes the georelational model. This approach does not incorporate the design of any other GIS table formats.

Module 4—VPFVIEW Application Software

This module teaches the VPFVIEW system architecture. Topics include software design and documentation, coding philosophy, the philosophy that drives specific designs, programming environment, software functionality, data flows, and data structures used to draw features. Tools from the VPFVIEW toolbox for program control and graphics, file interface, system and selection/queries, and menus are introduced. The principles of software maintenance are reviewed.

Module 5—VPF Training Seminar

This seminar is designed for advanced technical DMA staff with experience in VPF design and structures. A list of topics is to be agreed to prior to the beginning of this seminar. Topics for the seminar will be a subset of those provided in Modules 2 and 3.

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Appendix E. Acronyms

AML	ARC Macro Language
ANSI	American National Standards Institute
CAS	Chicago Aerial Survey
CD–ROM	Compact Disc–Read Only Memory
CG	City Graphic
CMAS	Circular Map Accuracy Standard
DAFIF	Digital Aeronautical Flight Information File
DCW	Digital Chart of the World
DEM	Digital Elevation Model
DGIWG	Digital Geographic Information Working Group
DIGEST	Digital Geographic Information Exchange Standard
DLG	Digital Line Growth
DMA	Defense Mapping Agency
DMAAC	Defense Mapping Agency Aerospace Center
DMASC	Defense Mapping Agency Systems Center
DMI	Disc Manufacturing, Inc.
DNC	Digital Nautical Chart
DOD	Department of Defense
DPI	Dots Per Inch
DPS	Digital Production System
DTED	Digital Terrain Elevation Data
DXF	Data Exchange Format
EGA	Enhanced Graphics Adapter
ESRI	Environmental Systems Research Institute, Inc.
FACC	Feature Attribute Coding Catalogue
FACD	Feature Attribute Coding Dictionary
FACS	Feature Attribute Coding System
FIPS	Federal Information Processing Standard
GIS	Geographic Information System
GUI	Graphical User Interface
JNC	Jet Navigation Chart
JOG	Joint Operations Graphic
LDSA	Loral Defense Systems—Akron
NOAA	National Oceanographic and Atmospheric Administration
NOS	National Ocean Survey
NOSC	Naval Ocean Systems Center
NRL	Naval Research Laboratory
ONC	Operational Navigation Chart
QA	Quality Assurance
QC	Quality Control
RAM	Random Access Memory
RFC	Request for Change
RGB	Red, Green, Blue
RMS	Root Mean Square

SCSI	Small Computer Standard Interface
SDTS	Spatial Data Transfer Standard
SML	Simple Macro Language
SOP	Standard Operating Procedure
SOW	Statement of Work
SPCS	State Plane Coordinate System
SPTS	Spatial Project Tracking System
TIGER	Topologically Integrated Geographic Encoding and Referencing [System]
TPC	Tactical Pilotage Chart
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
VPF	Vector Product Format
VPS	Vector Product Standard
VRF	Vector Relational Format
VSM	Vector Smart Map

Appendix F. DCW Project Deliverable Items

Deliverables associated with various sections of this report are listed below in order of discussion. If a variety of interim versions of a particular report were submitted, only the completed, final report is listed.

Section 2.2.1: Prototype 1 (12/19/89)

Prototype 1 database (on floppy disk)

PC ARC/INFO software and licenses

Evaluation instructions

Lithographic maps and color plots of the database

Section 2.2.2: Prototype 2 (4/9/90)

Prototype 2 database (on floppy disk)

Evaluation instructions

Lithographic maps and color plots of the database

Prototype 2 DCW applications software

Section 2.2.3: Prototype 3 (8/2/90)

Prototype 3 database (on CD-ROM)

Installation instructions

Evaluation instructions

Prototype 3 DCW applications software

Section 2.2.4: Prototype 4 (12/4/90)

Prototype 4 database (on CD-ROM)

Evaluation instructions

Lithographic maps and color plots of the database

Prototype 4 DCW applications software

DCW Users Manual (Prototype 4 Version)

Section 2.2.4: DCW Product Specification

DCW Product Specification (10/21/91)

Revised DCW Product Specification (Vegetation)—(12/4/91)

Military Specification—Digital Chart of the World (DCW), MIL-D-89009, 13 April 1992

Section 2.3.1: Aeronautical Information Study

Aeronautical Information Study (6/25/90)

Section 2.3.2: Elevation Data Study

Elevation Data Study (6/25/90)

Section 2.3.3: Tile Design Study

Tile Design Study (11/29/90)

Section 2.3.4: Indexing Studies

Indexing Studies: Coverage, Thematic, Gazetteer, Spatial Query (2/27/91)

Section 2.3.5: Geographic Organization Study

DCW Geographic Organization (9/27/91)

Section 2.3.6: Symbolization Study

Symbolization Study (6/12/91)

Section 2.3.7: DCW Error Analysis Study

DCW Error Analysis Study (2/15/91)

Section 2.4: Vector Product Format Military Standard

VPF Military Standard (6/28/91)

VPF Military Standard Request for Change (11/18/91)

VPF Military Standard (Version 0.8) (3/5/92)

Vector Product Format Military Standard, MIL-STD-600006, 13 April 1992

VPF Design Manual (5/30/92)

Section 2.5: VPFVIEW Software Development

DCW Application Software Report (3/14/91)
First VPFVIEW-DOS Software Prototype (5/24/91)
Second VPFVIEW-DOS Software Prototype (10/14/91)
VPFVIEW-DOS Functional Description (10/14/91)
VPFVIEW-DOS Functional Test Plan (Parts 1 and 2) (1/30/92)
VPFVIEW Users Manual for the DCW (1/30/92)
VPFVIEW-UNIX Functional Requirements (3/16/92)
VPFVIEW-DOS Version 1.0 (3/30/92)
VPFVIEW-DOS Functional Test Report (3/30/92)
VFPVIEW-DOS Applications Software Report (4/16/92)
VPFVIEW-DOS Integration Test Report (4/24/92)
System Design Document for VPFVIEW-UNIX (4/10/92)
Detailed Design Document for VPFVIEW-UNIX (4/29/92)
VPFVFIEW-UNIX (Alpha) (6/26/92)
VPFVIEW-UNIX—Multi-Library Functional Requirements (7/2/92)
VPFVIEW-UNIX—Multi-Library Design (7/17/92)
VPFVIEW-UNIX—Multi-Database Functional Requirements (9/4/92)
VPFVIEW-UNIX—Multi-Database System Design (9/4/92)
VPFVIEW-UNIX—Multi-Database Detailed Design (10/92 prop.)
VPFVIEW-UNIX—Multi-Database Version 1.0 (12/92, prop.)

Sections 3.1 through 3.8: DCW Production

DCW Production Plan (12/4/90)
DCW Standard Operating Procedures (1/4/91)
DCW Package Design (3/14/91)
Production System Description (3/28/91)
Revised DCW Standard Operating Procedures (5/10/91)
DCW Standard Operating Procedures Part 3 (10/5/91)
Revised DCW Package Design (11/11/91)
Revised DCW Standard Operating Procedures (Vegetation) (12/13/91)
Final DCW Standard Operating Procedures (1/15/92)
DCW CD-ROM Preliminary Disc A (1/30/92)

DCW CD-ROM Preliminary Disc B (2/28/91)
DCW CD-ROM Preliminary Disc C (3/4/92)
DCW CD-ROM Preliminary Disc D (4/20/92)
DCW Sets (Lot 1—150 Units) to DMA (7/28/92)
DCW Sets (Lot 2—1,500 Units) to USGS (7/31/92)
DCW Sets (Lot 2—3,000 Units) to DMA (8/4/92)
DCW Sets (Lot 3—1,850 Units) to United Kingdom (8/5/92)
DCW Sets (Lot 3—3,000 Units) to Canada (8/18/92)
DCW Sets (Lot 3—500 Units) to Australia (8/19/92)

Section 3.9: DCW Quality Assurance

Quality Assurance Plan (3/18/91)

Section 3.10: Desert Shield/Desert Storm Support

Database of Kuwait City (10/20/90)
Database of Baghdad (10/18/90)
Database of Persian Gulf (from Joint Operations Graphics) (12/17/90)
Database of Persian Gulf (from Tactical Pilotage Charts) (12/17/90)
ARC/INFO data dictionary for 1:250,000 digital JOG

Section 4.1: Digital Nautical Chart (DNC)

DNC Phase 1A: Floppy Disk Data Sampler (11/22/91)
DNC Phase 1B: Magnetic Tape Data Sampler—Norfolk, VA (1/1592)
DNC Phase 2: CD-ROM data sampler—Norfolk, VA (6/30/92)
DNC Phase 3: CD-ROM data sampler—Norfolk, VA and New York, NY (11/92, prop.)

Section 4.2: Vector Smart Map (VSM)

Prototype 1 Medium-Resolution VSM Product Specification (10/92, prop.)

Prototype 1 High-Resolution VSM Product Specification (10/92, prop.)

Prototype 1 VSM Database (Texas and Bolivia) (10/92, prop.)

Prototype 2 Medium-Resolution VSM Product Specification (1993, prop.)

Prototype 2 High-Resolution VSM Product Specification (1993, prop.)

Prototype 2 VSM Database (Texas and Bolivia) (1993, prop.)

Other Significant Deliverables

Configuration Management Plan (2/23/90)

DCW Audio Visual Tape (4/3/92)

DCW Training Plan (8/27/92)

ARC/INFO-to-VPF Converter Programmer Documentation (9/21/92)

Development of the DCW (9/25/92)